TANKER FUEL CONSOLIDATION:
EFFECTS OF HIGHER FIDELITY MODELING ON A RESILIENT PLAN

GRADUATE THESIS

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Abstract

The United States Air Force (USAF) has selected the KC-46 to begin replacing the aged KC-135 fleet. One of the major differences between the KC-46 and the KC-135 is the KC-46's ability to be refueled. This allows for tanker fuel consolidation, or the refueling of one tanker by another. The effects of this capability on the efficiency of tanker operations must be quantified and included in determining an appropriate substitution ratio between the two aircraft. This ratio will be used to plan the retirement of KC-135s as the KC-46 enters operational fielding. This study utilizes simulation to determine the efficiencies gained by consolidation while maintaining a desired operational resiliency. The time fidelity of the model was also increased to determine the effects on the results. Air Mobility Command's (AMC) Analysis and Assessments Division (AMC/A9) provided a problem set for the simulation. The results of this study show that the largest benefit is realized by the ability of the tankers to transition between altitudes within a refueling track, rather than being restricted to the same altitude as is done in current models. Tanker consolidation and the increased time fidelity did not provide statistically different results. The effects stated in previous studies focused on post-mission data, not planning data. The lack of a significant decrease in the number of aircraft required shows that the benefits of tanker consolidation are much greater when it is used as an execution tool, rather than a planning tool. While the number of aircraft

required in execution may be significantly decreased, the number required to meet the planning requirements is not.

This is dedicated to my wife and my sons.

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Jason Larimore

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I. Introduction

Background and Motivation

The KC-135 entered service in 1956 as the Air Force's primary air refueling platform. There are currently 415 KC-135s in service with the Active Duty, Air Force Reserve, and Air National Guard (USAF, 2009). After over 50 years in service, a plan for replacing these aging aircraft was pursued. The KC-X program was initiated in 2001 to begin recapitalizing the Air Force's KC-135 fleet (Brisson, 2010). On Feb 24, 2011, Boeing was awarded a contract to build 179 KC-46As to be the Air Force's new tanker aircraft (Flightglobal, 2011).

As the KC-46 enters service, the Air Force will begin to retire KC-135 aircraft. Air refueling plays such an important role in achieving the Air Force's strategic doctrine, determining the correct number of aircraft to retire, while maintaining the current capabilities, is paramount. Air Force Doctrine Document (AFDD) 2-6.2 states:

> Air refueling is an integral part of global mobility and brings added capability to combat, combat support, and air mobility aircraft for all airpower operations…Air refueling enhances the unique qualities of airpower across the full spectrum of military operations (12-13).

The factors used to determine the number of KC-135s to retire must be thoroughly examined for validation. Based off fuel capacity and fuel consumption, the KC-46 has been estimated to be equivalent to 1.14 to 1.38 KC-135s (Grismer, 2011). However, this estimation does not include the ability of the KC-46 to be refueled. This capability allows for a more efficient use of the KC-46 by capitalizing on its ability for fuel consolidation.

Fuel consolidation occurs when an airborne tanker does not have any further scheduled receivers, but still has fuel available to offload. The tanker can transfer that excess fuel to another airborne tanker. This increases the fuel available from that subsequent tanker. Fuel consolidation has been used during mission execution with KC-135s giving excess fuel to KC-10s and the few, air refueling capable KC-135s. It is estimated that during Operation Enduring Freedom (OEF), fuel consolidation caused the number of KC-10 missions to decrease by 20 percent (Isherwood, 2007). Thus far, this 20 percent has not held up under robust simulation. In his 2011 paper, Scott Linck wrote:

> AMC/A9 generated a number of studies to validate Isherwood's claim of 20 percent mission reduction through fuel consolidation. When applied to 'small' engagements with limited airfield availability, the models achieved the 20 percent reduction target but efficiencies eroded to 5 percent once the models grew to fit the scale of our recent engagement in Iraq (p. 2).

This study will continue and expand the work Linck started, by increasing the time-based factor fidelity of the model. This will provide planners with a more correct estimation of the efficiency that can be realized through fuel consolidation. The efficiency can then be applied to the factors being used to determine the number of KC-135s to retire as the KC-46 enters service.

One of the risks associated with increasing the efficiency of tanker missions is the loss of flexibility. The extra fuel in the airborne tankers has allowed flexibility for mission executors to quickly meet any unscheduled needs. As the schedule or Air

Tasking Order (ATO) becomes more efficient, it also becomes more brittle. Losing tankers during execution can cause failure of subsequent missions. In order for an ATO to provide a balanced mix of efficiency and flexibility, an appropriate level of resiliency must be chosen. This will allow the benefits of the efficiencies generated to be gained, while still ensuring overall mission success. This study will also provide an estimation of resiliency based on the efficiencies generated and different levels of risk.

Problem Statement

What levels of efficiency and resilience can be obtained through a tanker consolidation model?

> Efficiency will be measured by the difference in number of KC-135s required to meet the receiver demands. The resilience will be the level of efficiency that can be achieved at different levels of risk.

Hypotheses

Hypothesis 1: Incorporating tanker consolidation into planning will increase the efficiency of tanker utilization.

> Consolidation will allow the tankers to stay on track for longer periods of time, refuel more receivers per tanker, and provide more fuel for offload. This should reduce the number of tankers required to satisfy the receiver demand problem set.

Hypothesis 2: As time fidelity is increased in the model, the efficiency will decrease.

> Adding more detail to the model should increase its overall accuracy. The additional accuracy will include further limitations, which should in turn decrease the efficiency.

Hypothesis 3: Maintaining a desired level of resilience, while increasing risk, will decrease the efficiency of the model.

> Resilience is a balance of risk and organizational slack. Efficiency decreases organizational slack. This will lead to an inability to offset the level of risk, therefore lowering the level of resilience. To maintain the desired level of resilience, efficiency will need to be sacrificed to counteract the risk.

Methodology

A simulation model was created to determine the number of KC-135 tankers required to meet the identified receiver demand. Treatment zero simulates KC-135 operations with current realities. This provides a new baseline to best match the models currently being utilized for planning. The first treatment of the study introduces the ability of the tankers to freely adjust altitudes within the air refueling track. There is no tanker consolidation. Tankers will refuel until they either have no more available offload or there are no more viable receivers. The second treatment introduces tanker consolidation into the model. If there are no further viable receivers, the tanker offloads its excess fuel to another tanker, if one is available. The third treatment introduces time adjustments for altitude changes to the model. The time required adjusting to different altitudes both for scheduled receiver refuelings and tanker consolidation is not captured in the second treatment. The final treatment includes crew duty day limitations on the model. Tanker consolidation provides the possibility that an aircraft could continue to receive fuel from other tankers and stay airborne for extended flight durations. This could lead to flight durations that exceed maximum crew duty day limitations. Each treatment is run using several different mission capable rates. Each mission capable rate is equal to the amount of risk that the plan will require additional tankers to meet the requirements.

Assumptions

Several assumptions are maintained for the model to provide a solution:

- The schedule provided by AMC/A9 is correct and provides the best solution currently available to meet the demand.
- The air refueling tracks and altitudes provided are notional and do not need to meet air space separation requirements.
- All receiver demands must be met by the model solution. This requires a resilience level of 100%.
- The following receiver demand inputs are fixed: begin air refueling time, end air refueling time, time to complete refueling, offload, and air refueling altitude.
- There are an infinite number of KC-135s available to meet the demand.
- All KC-135s in the model have the ability to consolidate fuel. Boom-configured KC-135s can offload or onload fuel during consolidation. Drogue-configured KC-135s can only onload fuel.
- Multi-Point Refueling configured KC-135s are not included.
- Tankers can adjust altitude within their respective anchor without any additional deconfliction limitations, but may not transit to other anchors.
- The mission capable rates will represent all tanker aborts, no matter the reason. This will include ground aborts or air aborts; to include maintenance aborts, weather aborts, or crew aborts.

The solution provided by this model is representative of the KC-135 role in an air campaign equivalent to the recent conflicts in Afghanistan and Iraq. There are many different types of KC-135 missions and force mix options available to planners. This solution may not be applicable to every future campaign.

The second chapter of this study focuses on a review of literature applicable to the subject. The third chapter describes the methodology used during the study. This will include a description of the model itself, the input variables used, and the treatments for each run of the model. The fourth chapter analyzes the results presented by the model solutions and how they compare to the study's hypotheses. The final chapter presents applications for the results, future areas of study, and limitations of the study.

II. Literature Review

KC-135 Employment

For over fifty years, the KC-135 has been the USAF's primary air refueling platform. In the beginning, its primary mission was supporting the strategic bombing capability of Strategic Air Command. Over the years, the capabilities and mission have increased as new uses for the aircraft are found. Currently, the KC-135 missions are: theater combat support, global strike support, fighter coronets, channel airlift, aeromedical evacuation, and it even carries datalink nodes to increase battlefield communication capabilities (Department of the Air Force, 2010). This study focuses on the theater combat support mission. Air refueling provides Combatant Commanders with greatly increased capabilities. The KC-135 has been termed a force multiplier and provides essential capabilities for the way air power is employed in combat (Department of the Air Force, 1999). It reduces the number of aircraft required to complete a mission and provides for increased surveillance coverage by allowing aircraft to remain on station for greater periods of time. It also allows targets at greater distances to be engaged by enabling aircraft to reach these targets. The ability for combat aircraft to carry larger payloads is another benefit of air refueling.

The KC-135 has three primary configurations that can be used to support combat missions. The first configuration utilizes boom and receptacle air refueling. This type of air refueling is primarily utilized by USAF receiver aircraft. The KC-135 boom operator flies the boom nozzle into the receiver's receptacle, and then fuel is passed into the receiver aircraft. This configuration provides the greatest maximum fuel transfer rate, up to 6000 pounds per minute (North Atlantic Treaty Organization, 2010). The second configuration is the probe and drogue. This configuration requires that a drogue hose and basket be attached to the end of the boom. This method primarily supports US Navy and foreign ally receiver refueling. During this procedure, the boom operator holds the boom stable and the receiver effects contact by maneuvering a probe into the drogue basket. This method has a reduced maximum fuel transfer capability of 2800 pounds per minute (North Atlantic Treaty Organization, 2010). Aircraft configured in either of these two manners do not have the capability to support the other type of air refueling during the same mission. The final configuration incorporates both of the methods of refueling. By mounting Multi-Point Refueling System (MPRS) pods on the wings, the KC-135 can support both boom refueling and probe and drogue refueling on the same mission. This greatly increases the flexibility of the aircraft for commanders and planners. However, only twenty wingpod kits were purchased. This limited availability has caused the MPRS to be treated more as a bonus than a standard planning factor. Because of this, this study only includes boom or probe and drogue configured aircraft.

There are several different types of air refueling tracks utilized by KC-135 aircraft. An air refueling track is the reserved airspace that is used by the tanker and receiver aircraft while refueling. Air refueling tracks mostly follow two configurations. The first is a long, linear track where the aircraft meet at one end and fly a linear path to an exit point. This requires a great deal of horizontal airspace to be reserved for the air refueling. It is generally used for longer range, strategic refueling missions. The primary type of track utilized during theater combat support missions is the anchor (Department of the Air Force, 2010). The anchor is generally an oval, racetrack-shaped track that minimizes the amount of airspace required for air refueling (see Figure 1). It allows for maximization of the vertical airspace by stacking several tracks at different altitudes within the same horizontal borders. It also provides planners an ability to maximize the airspace around a target area.

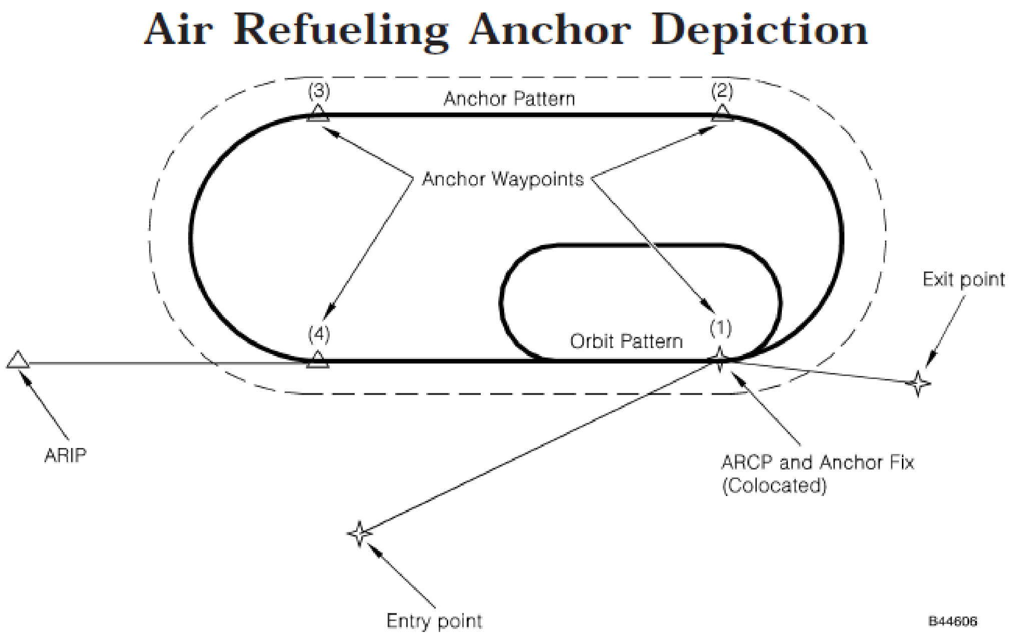


Figure 1: Anchor Track (Department of Defense, 2011)

The amount of fuel available to be offloaded to receivers during a mission is dependent on several factors. The KC-135 has a maximum fuel capacity of 200,000 pounds. This total fuel amount includes both the fuel for offload and the fuel the KC-135 will burn itself while airborne. The fuel available is what is left over after subtracting the fuel to get to the air refueling track, remain on station, and return from the track from the takeoff fuel level. The takeoff fuel level is determined for each base that the KC-135s will launch from. It is based off runway length and weather conditions. This study focuses on KC-135s from a single launch base, which provides for standard fuel availability.

Modeling

Mathematical models allow us to study systems on a smaller scale and lower cost than actual trials. In their book, *Simulation with Arena* (2010), Kelton, Sadowski, & Swets define a model as "…a set of approximations and assumptions, both structural and quantitative, about the way the system does or will work." There are several modeling tools available. They can be technologically simple, such as differential-equations, queuing theory, spreadsheets, and linear programming. They can also be technologically complex, such as the numerous software packages available for purchase.

Models can be built to represent various levels of complexity in a system. The purpose behind the model determines the level of complexity within the model. Models can also be used to support or even automate decision making. In his article, "Why Modeling and Model Use Matter (2010)," Pidd proposes two extremes in modeling complexity. The first, and simplest, is used to lead an experimenter in a general direction, like a compass. This starts them on a direction of exploration and can assist in decision making, but does not give an accurate solution. The second, and most complex, gives an extremely accurate solution, like a global positioning system (GPS). These solutions can be used to provide complete support to decision making. Compass-level simulation gives just one small input for a user to consider when finding a path to their destination. GPS-level simulation gives a precise path that leads the user to the destination. It can be the sole input into decision making. Most models fall somewhere in the spectrum between these two extremes. Pidd defines four primary archetypes for modeling, based on their uses:

- Modeling for Decision Automation
- Modeling for Routine Decision Support
- Modeling for Investigation and Improvement
- Modeling to Provide Insights

The model created for this study is an Investigation and Improvement model. This type of model "…is an artificial world in which options can be compared, experiments conducted, and investigations made without risk of damage or serious expense" (Pidd, 2010). This study examines KC-135 aircraft that can be refueled, a configuration that does not exist in the real world for all of the KC-135 aircraft. Attempting to experiment using actual aircraft would incur extreme levels of cost in aircraft modifications, aircrew, and aircraft usage. This type of model allows us to "what if" this scenario with the only cost being the experimenter's time and effort.

Simulation

An increasingly popular tool is computer simulation. The popularity has grown as computer software capability has increased and price has decreased. This allows a greater number of users to solve complex problems using this software. Kelton et al. define simulation as "…the process of designing and creating a computerized model of a real or proposed system for the purpose of conducting numerical experiments to give us a better understanding of the behavior of that system for a given set of conditions" (2010). Simulation allows us to manipulate inputs and capture the resulting changes that are made on a system. Simulation has been found to be especially useful in studying complex systems (Kelton, Sadowski, & Swets, 2010).

One feature of simulation that is especially helpful is the ability to introduce randomness into the model. Real systems do not produce consistently perfect output. Even a robotic assembly line controlled by computers can experience randomness. A power failure or software glitch could cause activity along the whole line to stop; therefore disturbing the mechanical perfection of the line's output. This inherent randomness must be accounted for in a simulation. These stochastic inputs also provide for randomness in the solutions provided by the simulation. Assumptions can be introduced to the simulation to combat randomness. However, this leads to a model that does not reflect the real system and is therefore not valid (Kelton, Sadowski, & Swets, 2010). In this study, randomness is introduced through the abort rate of aircraft. The other inputs were predefined by the experimenter and approved by the study's sponsor.

The abort rate is determined by subtracting the mission capable rate from 100 percent:

$$Rate_{abort} = 100 - Rate_{mission\ capable}$$

This abort rate accounts for any aircraft cancelation, whether on the ground or airborne. There are many factors that can lead to an aircraft abort, including aircraft malfunctions, weather, and aircrew issues. Aircraft malfunctions are difficult to predict with accuracy because of the multitude of parts and ways they can fail. Weather is also not easily predicted at the launch base or in the air refueling track. Conditions that are favorable can quickly exceed limitations with little warning. Aircrew issues can arise due to illness or injury. Predicting when these will arise is difficult due to the accidental nature of many injuries and unpredictable nature of some illnesses. These randomly occurring events can affect the number of aircraft needed to satisfy receiver demands and must be accounted for in the simulation.

Simulation has been used in many different fields of study and industries. The majority of early simulations focused on manufacturing systems (Tavakoli, Mousavi, & Komashie, 2008). As the capabilities have become more widespread, other industries have begun to put this tool to use. One of the popular uses for simulation, no matter the industry, is scheduling. The solution provided by the simulation in this study is an air refueling schedule for the KC-135s from a launch base. Scheduling problems have been studied using simulation in several industries. Hani et al. (2008) used simulation to create an optimized schedule for a railway maintenance facility. This simulation resulted in an 18% improvement in facility throughput. Tavakoli et al. (2008) used discrete event simulation to demonstrate the usefulness to both manufacturing and non-manufacturing systems. They built simulations that provided solutions for a manufacturing shop floor schedule and also for patient handling in a hospital emergency department. Sometimes simulation can be used to examine some of the factors that are used as inputs to the scheduling model. Adeleye and Chung (2006) used simulation to analyze turnaround operations at the departure gate for an airline. When developing a schedule for an airline, it is important for them to know how long an aircraft will need for passengers to deplane and get the aircraft reconfigured, refueled, and reloaded with outbound passengers and baggage. This simulation allowed them to test several contingencies that could affect this timing.

Arena

One tool available for computer simulation is Arena software. Arena is a software simulation package produced by Rockwell Automation. This software package "…combines the ease of use found in high-level simulators with the flexibility of simulation languages and even all the way down to general purpose procedural languages like the Microsoft® Visual Basic® programming system…" (Kelton, Sadowski, & Swets, 2010). This range of operability allows users with various levels of computer skills to utilize this software for simulation. Templates are provided that represent many generic functions and processes found in systems. Users can customize these generic templates by defining inputs using probability distributions, constants, or mathematical expressions.

Tanker Simulation Studies

Tanker requirements have been the subject of previous Arena simulation studies. Neither of the simulations used in these previous studies provide the level of fidelity desired for this study, but both provided direction in building this study's model.

Gates and McCarthey (1999) used Arena to determine the Marine Corps' future KC-130 requirements. This study proved that simulation was a valid tool in studying tanker operations. The Marine Corps' much smaller tanker fleet and employment of air refueling limited the scale of this study. The operations studied only covered two air refueling anchors. Also, the focus was on limiting the receiver wait time and ensuring that the anchor always had a tanker on-station (Gates & McCarthey, 1999).

Linck's study (2011) examined the effects of tanker consolidation on ATO resiliency. It used the same receiver requirements and CMARPS-developed solution as the current study. It was the inspiration for this study and provided a starting point for the determination of the KC-46 requirements to replace the KC-135. Using the compass and GPS comparison of models presented earlier, it is closer to the compass on the spectrum. This study proposes to expand on this earlier study and provide a model that falls closer to the GPS on the spectrum. Linck's model incorporated several assumptions that require further exploration in order to more accurately represent the real system. The first assumption is the lack of aircraft aborts represented in the model. This assumption removed the randomness from the simulation. Aircraft aborts happen in the real world, and therefore need to be represented in a more robust model to provide increased validity.

Next, it was assumed that receiver aircraft would adjust timing to accommodate the KC-135s. This helped to increase the efficiency of the solution, but does not align with the realities of tanker planning. Receiver refueling times are based off requirements to meet timing for the strategic objectives chosen earlier in the ATO cycle (Winkler, 2006). Adjusting air refueling times can have far-reaching effects on that day's operations planning. This study holds the receiver timing requirements as fixed and provides a solution representative of this reality. A third assumption was that the KC-135s would fly the same sortie duration as in the CMARPS solution. As previously discussed, one of the benefits of tanker consolidation is that it allows a tanker to stay airborne for longer periods of time. Therefore, this study includes increased flight duration as a factor in the simulation. Finally, it was assumed that probe and drogue configured KC-135s would not be accounted for in Linck's simulation because of their inability to give fuel to other KC-135s during tanker consolidation. These aircraft are capable of receiving fuel during tanker consolidation, which can affect the number of aircraft needed in the solution because some of the receivers listed in the requirements can only perform probe and drogue refueling. These differences provide for higher-fidelity and increased complexity of the model, presenting a more accurate and valid model.

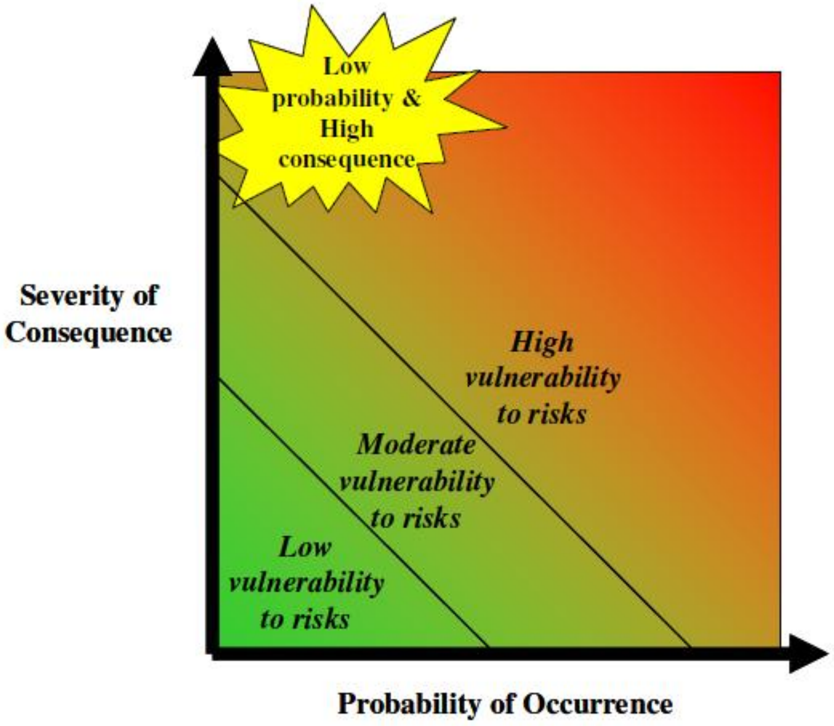
Resiliency

One of the desired outcomes of tanker consolidation is to increase the efficiency of a tanker planning solution. Whenever efficiency is increased, the probability of a plan failing is also increased. Efficiency is a measure of the ability to provide a given outcome using a corresponding level of input. The lower the input required to produce that output, the greater the efficiency. A higher level of input results in a lower efficiency. For this study, inputs are represented by the number of KC-135s and the desired level of output is all the receiver refueling requirements being met. The more efficient a process becomes, there are less extra inputs available to meet a contingency. These excess inputs are known as organizational slack. Bourgeois (1981) defined organizational slack:

> Organizational slack is that cushion of actual or potential resources which allows an organization to adapt successfully to internal pressures for adjustment or external pressures for change in policy, as well as to initiate changes in strategy with respect to the external environment.

Organizational slack provides a buffer against disturbances in the system. The higher the level of efficiency for a system, the lower the level of organizational slack becomes. This increases the probability that a disturbance will cause the system to fail.

The probability of failure can also be thought of as risk. Risk is defined as "someone or something that creates or suggests a hazard" (Merriam-Webster, 2011). Manuele (2005) asserts that risk level is a function of the probability of the hazard occurring and the severity of harm that could result. Petit et al. (2010) developed a visual depiction of this (see Figure 2).



Adapted from Manuele (2005).

Figu

re 2: Risk Diagram

For this study, risk is best defined by the probability of aircraft aborts. An abort forces another tanker to meet the requirements that the aborted tanker would have met. This could lead to additional tankers being required to meet the demand. The abort rate is equal to the probability of occurrence. The severity of consequence is represented by the increase in resources (tankers) needed to meet the requirements. A balance of the risk with the resources available must be determined.

Resilience is a concept that can help determine the balance required between risk and available resources. Fiksel (2006) defined resilience as "…*the capacity for an* *enterprise to survive, adapt, and grow in the face of turbulent change*." In the case of a military operations plan, resilience can be thought of as the ability to absorb disturbances and yet result in the strategic objectives being achieved. For the KC-135 daily schedule, resiliency is the ability to absorb aircraft aborts and still meet all of the receiver fuel demands. The additional capability of extra aircraft balances the risk of a higher aircraft abort rate. The cost of failing to maintain capability at a level to balance the risk for military operations is high. It is not just paid for in failed objectives. In endangers the men and women fighting in the air, on the ground, and at sea.

Petit et al. (2010) developed a framework for ensuring supply chain resilience. They proposed that "Linkages exist between each vulnerability and a specific set of capabilities that can directly improve balanced resilience" and that "Supply chain performance improves when capabilities and vulnerabilities are more balanced" (Petit, Fiksel, & Croxton, 2010). They also defined a "Zone of Resilience" that supply chains could operate within to balance risk and resources (see Figure 3).

Figure 3: Resilience (Petit et al., 2010)

Operating in this zone provides the required amount of capability, or resources, to withstand a given level of risk. This framework can be applied to this study. For the purpose of this study, the capability is represented by the number of KC-135s required to meet the receiver demand. The vulnerability is represented by the abort rate. The desired level of resilience is for all receiver demands being met, or right in the center of Zone of Resilience. Erosion of profits is represented by a decrease in the efficiency of the solution. Exposure to risk is represented by the exposure to the operation failing if all receiver demands are not met. This objective to this study can be adapted to this framework by asking: What level of capability must be provided, given a desired level of resilience and an acceptable level of vulnerability?

III. Methodology

Introduction

In order to launch this experiment, a data set was required to provide requirements for the simulation to fulfill. AMC/A9 provided a problem set and solution using the Combined Mating and Range Planning System (CMARPS). CMARPS generated the receiver requirements, an ATO solution, and a schedule for an operation equivalent to those the USAF has recently been engaged (such as Operations Enduring Freedom and Iraqi Freedom). It includes refueling conducted from 12 tanker bases of origin and 23 air refueling tracks. Because of the extremely large scale encountered, it was determined through discussion with the research sponsor to conduct the experiment using only the air refueling events tasked to a single tanker origin base. Base KA04 was chosen for the experiment. It was tasked to support refueling events on all of the tracks and with both boom refueling and probe and drogue refueling. The CMARPS solution for Base KA04 included the following data:

- Total Refueling Events: 723
- Total Fuel Offloaded: 14,090,400 pounds
- Total Receiver Aircraft Refueled: 2333
- Total Tankers Required: 222
- Average Fuel Offloaded Per Tanker: 63,470 pounds

AMC/A9 also included flight plans to and from each track to help determine timing and fuel consumption. It was determined that this experiment would only utilize the receiver requirements and flight plans provided. The ATO solution and schedule provided by

CMARPS gave a good reference point, but could not be used to accurately compare against for validation. As previously noted, simulation that includes factors that do not exist in the real system does not allow for accurate validation against the real system. Further, there were several functions imbedded in CMARPS that were not feasible for inclusion in this simulation (examples: actual flight planning software versus fuel burn planning factors, scenario-specific minimum reserve fuels versus utilizing all fuel available, tanker maintaining the same refueling altitude versus transitioning between altitudes as needed). It was determined that while excluding these functions would not allow comparison, the simulation still provides a valid representation of the system. Table 1 depicts an example of a schedule for Anchor 01 created from the CMARPS solution. Establishing a new baseline will provide an accurate value of the efficiency and resiliency of tanker consolidation.

Table 1: Sample Schedule Created from CMARPS Solution

Callsign	Configuration	T/O Time	Land Time	Altitude	AR Start Time	AR End Time	Receiver Request #	Receiver Type	# of Receivers	Offload
Tanker 1-1	Boom	56	411	25000	117	128	185	FA22	2	10500
				25000	191	249	186	FA22	6	31500
				25000	286	322	187	FA22	4	21000
				25000	365	376	188	FA22	2	10500
	Flight Duration	355						Total	14	73500
Tanker 1-2	Boom	106	512	15000	166	176	164	A10A	2	7100
				15000	235	245	165	A10A	2	7100
				15000	305	315	166	A10A	2	7100
				15000	378	405	167	A10A	4	12400
				15000	465	475	168	A10A	2	6200
	Flight Duration	406						Total	12	39900
Tanker 1-3	Boom	247	663	16000	307	317	172	A10A	2	6200
				16000	473	483	173	A10A	2	6200
				16000	546	556	174	A10A	2	6200
				16000	616	626	175	A10A	2	6200
	Flight Duration	416						Total	8	24800
Tanker 1-4	Boom	359	575	25000	420	450	189	FA22	4	21100
				25000	455	505	190	FA22	8	35300
				25000	528	539	191	FA22	2	10500
	Flight Duration	216						Total	14	66900
Tanker 1-5	Boom	406	668	19000	467	478	176	F16C	2	7700
				19000	507	518	177	F16C	2	7700
				19000	547	558	178	F16C	2	7700
				19000	621	632	179	F16C	2	7300
	Flight Duration	262						Total	8	30400

In order to provide a comparison, the simulation first needs to be run without tanker consolidation. A separate simulation is run for each air refueling track. A complete treatment is run for each individual track. The results for each track are analyzed to determine the mean number of KC-135s required for that track. The means are rounded to the nearest whole integer, to reflect that partial airplanes do not exist in the real system. The means for all the tracks are then added together to determine the total number of KC-135s for the scenario.

Treatment zero provides a new baseline for comparison and introduces the main model. The first treatment allows the tanker entities to freely adjust altitudes within the anchor to be matched with any receiver entities. The second treatment introduces tanker consolidation to the simulation. The third includes time required for climbs and descents when the tanker adjusts altitude. The fourth incorporates crew duty-day limitations to the simulation. Each subsequent treatment utilizes the same model as the previous treatment, with additions that represent the intended changes to the system. Each treatment is run using four different abort levels: 0%, 5%, 10%, and 15%. The goal mission capable rate for KC-135s is 85% (United States General Accounting Office, 2003). The abort levels were determined at equal intervals between 100% and 85%. Each simulation run consists of 3 replications, each covering a 24-hour simulation period. The mean number of KC-135s required to meet all receiver requirements is calculated for each replication. The results are then analyzed to determine if this number of replications provides a statistically significant difference from the other treatments at the same abort level. If the difference is not significant, the number of replications required to prove significance is determined. If the number of replications required is feasible, the simulation is re-run for this number of replications.

Baseline Model

The baseline model is used to provide a solution for Treatment 0 and is the framework that the rest of the treatments build off of. Treatment 0 provides a representation of a solution that best matches the logic utilized by CMARPS. Treatment 0 was only run with a 0% abort rate because CMARPS does not utilize an abort rate when providing a solution. Only 1 replication was run because at this abort rate, there would be no difference between the replications.

Receiver Control Process

Figure 4: Depiction of the Receiver Control Process

The Receiver Control Process is used to control the release of receiver entities into the model's main process section by sending a unique signal. The Rel Receiver Demand module is used to create entities for this process. These entities represent the receiver demanded refueling events. They are released at a constant rate of 1 entity every second, with the first entity released at time 0. This is used to quickly generate a pool of entities at the outset of the simulation. The maximum number of entities is limited by the number of receiver requests for each refueling track. The Assign Start Time module is used to assign the attribute of "AR Start Time" to each of the entities. These attributes are read from an Excel® input spreadsheet (example in Appendix 3) and represent the start time for each receiver demanded air refueling event. The Hold Until Start Time module is a delay module that holds the entities until their assigned AR Start Time. Once the simulation time has reached an entity's assigned time, the entity will be released to the Signal to Release Receiver module. As each entity passes through the Signal to Release Receiver module, a signal of "1" will be sent to the receiver entities in the RCVR Wait Until AR Time module in the model's main process section. The entities then are disposed in the Dispose Receiver Demand module to complete the process.

Tanker Control Process

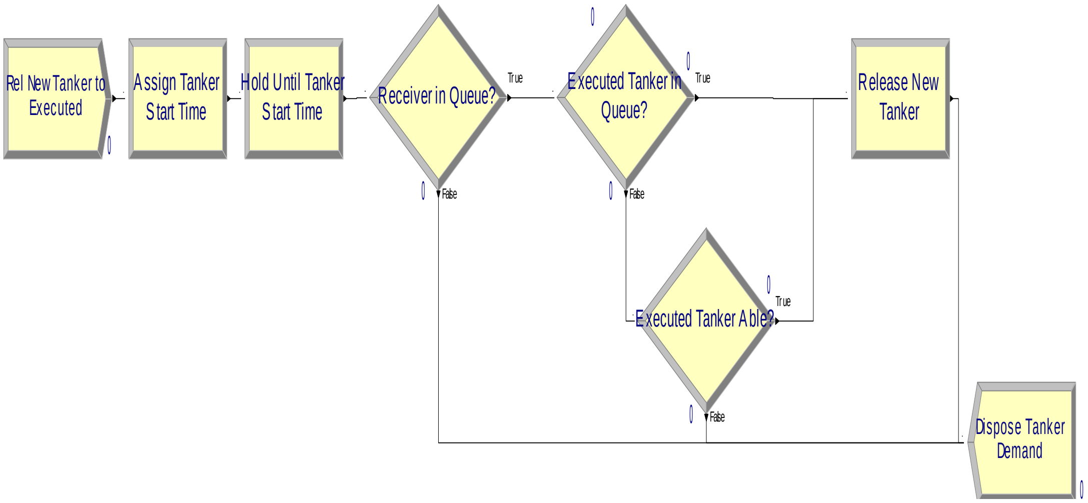


Figure 5: Depiction of the Tanker Control Process

The Tanker Control Process is used to control the release of tanker entities from the unexecuted tanker pool by sending a unique signal as needed. The Rel New Tanker to Executed module is used to create entities for this process. Entities are released at a constant rate of 1 every second, with the first creation at time 0. Again, this is used to build a pool of created entities quickly. The maximum number of entities is equal to the maximum number of receiver requests for that track as well. This will ensure an adequate number of tanker entities are created, as a 1 to 1 ratio of tankers to receivers is the maximum that is required for this problem set. The Assign Tanker Start Time module utilizes the same times and process as the Assign Start Time module in the Receiver Control Process. The Hold Until Tanker Start Time module is a delay module. This module releases entities at their AR Start Time plus .001 minutes. The additional time allows for any entities processing the model to complete their actions that occur at the same time point as the AR Start Time. Without this delay, new entities may be released even though an already executed tanker entity is available to complete the refueling event. These executed entities may be processing through other modules, but will be present in the Executed Tanker Pool module before the model moves on from that time point. For example, a tanker entity that has just completed a refueling event may still be processing through several modules to adjust attributes and record data on its way back to the Executed Tanker Pool. In the simulation, an entity may pass through several modules with no time passing. This delay ensures the proper sequencing of steps within the model. Once an entity is released in the Tanker Control Process, it passes through a series of decision modules to determine if a new tanker entity needs to be released to the pool of executed tankers. The Receiver in Queue? module is a 2-way by condition decide module. It looks at the Match queue and uses an expression to determine if any receivers are awaiting a tanker. If the condition is true, the entity continues to the Executed Tanker in Queue? module. If the condition is false, the entity proceeds to the Dispose Tanker

Demand module. This represents whether a receiver has already been matched with an executed tanker or not. The Executed Tanker in Queue? module is a 2-way by condition decide module. It looks at the Executed Tankers queue and uses an expression to determine if there is not an executed tanker entity available to be matched with the receiver entity in the Match module. If the condition is true, the entity continues to the Release New Tanker Module. If the condition is false, the entity proceeds to the Executed Tanker Able? module. The Executed Tanker Able? module is a 2-way by condition decide module. This module determines if the tanker(s) in the Executed Tankers queue is/are unable to fulfill the demands of the receiver in the Match queue. If the condition is true, the entity continues to the Release New Tanker module. If the condition is false, the entity is directed to the Dispose Tanker Demand module. The Release New Tanker module is a signal module that sends a signal of “2” through the model. Entities awaiting a “2” signal are then released from their respective queues. A limit of one signal per entity processing through the module is used to ensure that only the desired number of new tankers is released for execution. This signal is unique in that only entities in the Unexecuted Pool module in the main model are set to be released at this signal. The Dispose Tanker Demand module disposes of these entities to complete the Tanker Control Process.

Main Model

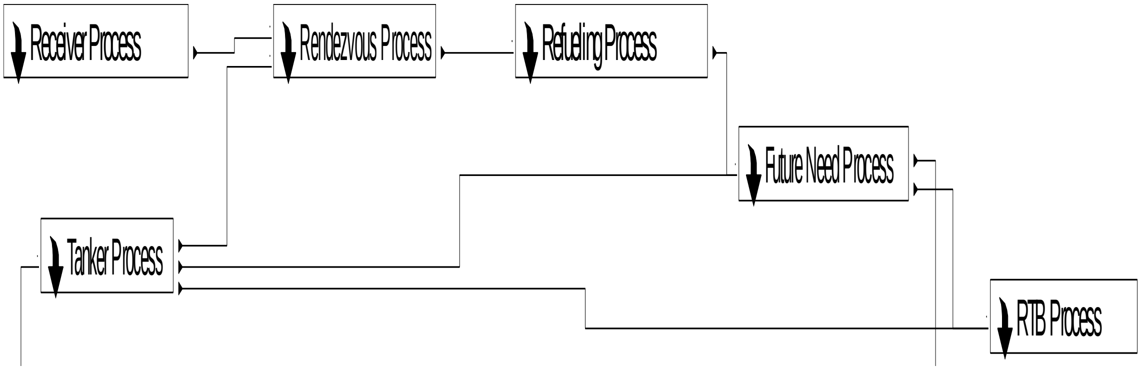


Figure 6: Depiction of the Main Model

The Main Model is representative of an air refueling system. It consists of six sub-models that are linked together. The following descriptions will step through the model in the same order that actions happen during simulation runs. First, the receiver process will be explained up to the point where the receiver is matched to a tanker. Then the tanker processes will be described up to the same point. Next, the join-up process will be examined. Following that, the air refueling process will be clarified. The post air refueling actions of the tanker then will be explained. Finally, the details of the tanker return to base process will be given.

Receiver Process

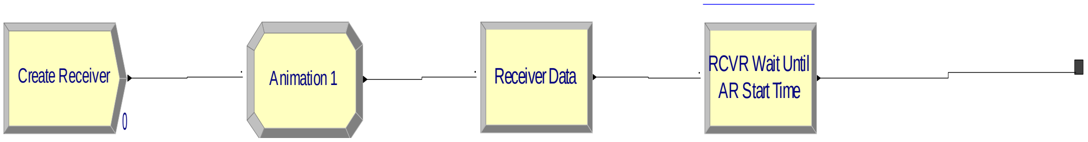


Figure 7: Depiction of the Receiver Process Sub-model

The Receiver Process Sub-model represents the actions of the receiver entities as they enter the model and await their air refueling times. The Create Receiver module creates the receiver entities. Entities are created at a constant rate of 1 every second, starting at time 0. The number of entities is limited to the number of receiver requests for each track. Each entity is representative of the receiver group for that receiver demand. Therefore, even if the actual receiver request included multiple receiver aircraft, the model only creates a single entity. The differences in numbers of aircraft are represented in the R AR Time attribute. This attribute represents the time required for the receivers to rendezvous with the tanker, receive all their fuel, and depart the air refueling track. In the schedule created from the simulation results, the actual number of aircraft in the receiver request is annotated. The Animation 1 module is used to give the entities an airplane animation. This will show the entities as airplanes as they move through the model. The Receiver Data module is used to assign attributes to the receiver entities. The following attributes are assigned from the same Excel® input file utilized for all model inputs: Configuration (probe & drogue or boom), Receiver # (for identification when building schedule), R AR Start Time (receiver beginning air refueling time), R Offload (in pounds of fuel), R AR Time (duration to complete air refueling event), and R Altitude (scheduled air refueling flight level). The RCVR Wait Until AR Start Time is a hold module. The entities will queue up based on their AR Start Times. This is a lowest attribute value queue. This ensures that the entities will be released at their appropriate AR Start Times. One entity is released every time a signal of “1” is sent from the Receiver Control Process. When released, the entities proceed to the Match module.

Tanker Process

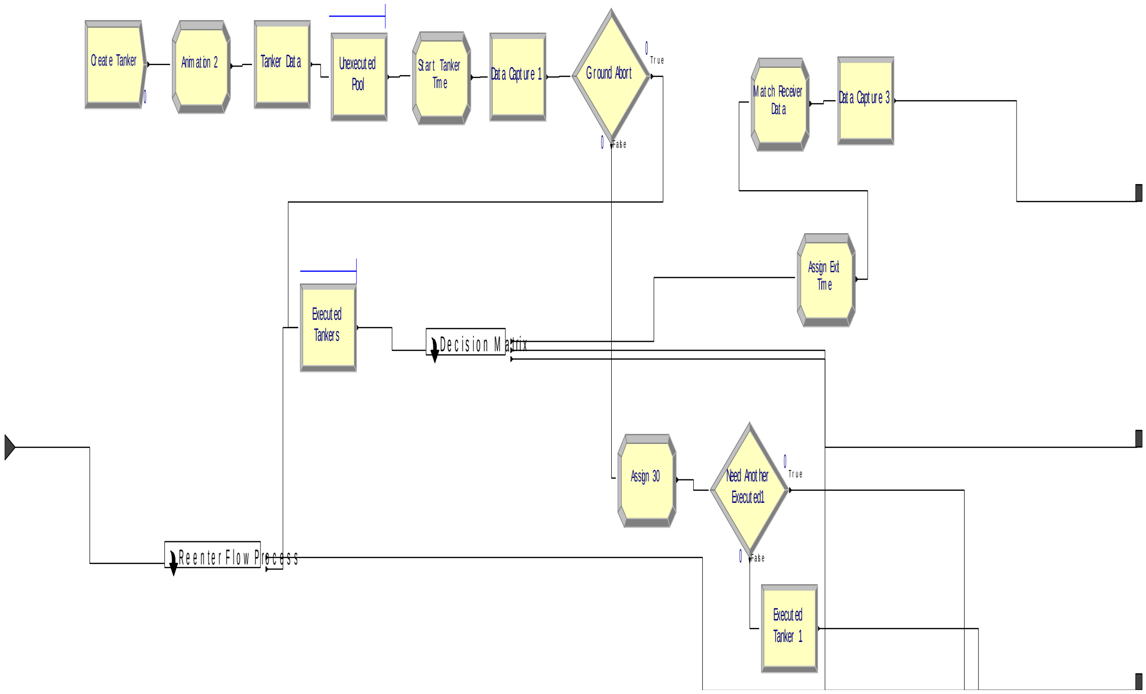


Figure 8: Depiction of the Tanker Process Sub-model

The Tanker Process Sub-model represents the actions of the tanker entities up to the point where they are matched with the receiver entities. The Create Tanker module creates tanker entities. Entities are created at the same rate as in the Tanker Control Process, with the same limitations as well. The only exception is that the maximum number of entities created is 73. Due to possible aborts, matching the number of tanker entities to the number of receiver entities would ensure enough tankers were created for some of the tracks that had a small number of receivers. The number used was representative of the largest number of receiver entities for any of the 23 tracks and ensures that enough tankers will be created to meet any needs, regardless of aborts. The Animation 2 module again gives the entity an airplane picture representation as it flows through the model. The Tanker Data module assigns a single attribute to the tankers. The attribute is assigned from the input spreadsheet. The attribute is Tanker # (will determine callsign). The entities will then enter the Unexecuted Pool. This is a hold module where the entities will queue up using a first-in, first-out priority. One entity will be released when a signal of “2” is sent from the Tanker Control Process. The release of each entity executes that entity into the model. It is representative of determining that another tanker would need to be launched to meet the receiver demands. The Start Tanker Time module is another assign module. These attributes are not assigned from the input spreadsheet. They are determined as the simulation runs (Configuration, Tanker Start Time, Altitude, and Enter Time) or are standard for all these entities (Fuel and Chance of Abort). The Configuration (1 for boom or 2 for probe & drogue) is the type of air refueling equipment the aircraft was configured with prior to mission launch. It is determined based off the Configuration attribute of the receiver in the Match module that caused the new tanker to be executed. The Tanker Start Time represents the time when the entity first enters the air refueling track and will not change throughout the model run. The Altitude is also given the same value as the receiver in the Match module that executed the tanker entity. The Enter Time represents when the entity enters the Executed Tanker Pool. This time will be updated every time the tanker enters the pool of executed tankers. Fuel is the standard initial fuel level for all tanker entities entering the track. It is determined by subtracting the fuel burned enroute to and from the track from the standard ramp fuel used for the base of origin:

$$Q_{Fuel} = Q_{Ramp} - Q_{Burned\ Enroute}$$

The ramp fuel for base KA04 was 200,000 pounds. The fuel burned enroute was determined from the flight plans provided by AMC/A9. Fuel levels for each track are listed in Table 2. The Chance of Abort assigns a random number between 0 and 1 (0 = 0% probability of abort, 1 = 100% probability of abort) to each entity. The random numbers are generated using a uniform probability distribution. The random number seed is changed for each replication of the simulation. Seed 1 is used for replication 1, 2 for replication 2, and 4 for replication 3 (using seed 3 resulted in excessive aborts, over 70% in some cases).

Table 2: Initial Fuel Levels

Track	Ramp Fuel (pounds)	Fuel Burned Enroute (pounds)	Initial Fuel Level (pounds)
1	200,000	24800	175,200
2	200,000	28300	171,700
3	200,000	30400	169,600
4	200,000	34500	165,500
5	200,000	27000	173,000
6	200,000	31400	168,600
7	200,000	23200	176,800
8	200,000	23400	176,600
9	200,000	21600	178,400
10	200,000	30500	169,500
11	200,000	30800	169,200
12	200,000	29500	170,500
13	200,000	25100	174,900
14	200,000	27800	172,200
15	200,000	28400	171,600
16	200,000	25400	174,600
17	200,000	30100	169,900
18	200,000	33900	166,100
19	200,000	34800	165,200
20	200,000	28200	171,800
21	200,000	34300	165,700
22	200,000	34700	165,300
23	200,000	40200	159,800

Data Capture 1 is a ReadWrite module used to capture data for verification of the model. It records the attributes Configuration, Chance of Abort, Tanker # and Tanker Start Time to the Excel® output spreadsheet (example can be found in Appendix 4). Once the tanker entities leave the Data Capture 1, they proceed to the Ground Abort module. This module is a 2-way by condition decide module. It represents the possibility of a ground abort. The percentage of chance that an entity does not abort was set at four different values: 100% (no aborts), 95% (5% abort rate), 90% (10% abort rate), and 85% (15% abort rate). If the entity's Chance of Abort is less than the abort level for that simulation run, it continues on to the Executed Tankers module. If the Chance of Abort is greater than the abort level, the entity proceeds to the Assign 30 module. This module assigns the attribute Aborted to the entity. The attribute value is 1 and allows for easy identification of aborted tankers for data analysis. Even though an entity is aborted, the receiver demand must still be met. Therefore, the entities proceed to the Need Another Tanker 1 module. This 2-way by condition decide module looks at the Executed Tanker queue to determine if another tanker needs to be executed to refuel with the waiting receiver. If there is 1 or more executed tankers in the queue, the entity continues on to the RTB Process sub-model. If there are no tankers in the Executed Tankers queue, the entity passes through the Execute Tanker 1 module. This allows a signal of "2" to be sent, releasing another tanker entity from the Unexecuted Tanker Pool. The entity then moves on to the RTB Process sub-model.

The Executed Tankers module is a Hold module that keeps the entities in a queue until they are released. The entities are queued based on first-in, first-out logic. Entities are released using a scan for condition logic. Whenever a specific condition exists in the model, an entity is released. If the number of entities in the Match module queue 1 (receiver entities) is greater or equal to 1, a single tanker entity is released. If there are no more receiver entities in the RCVR Wait Until AR Start Time queue, the remaining executed tanker entities are released so that they can proceed to the RTB Process sub-model to complete the simulation run.

Decision Matrix Sub-model

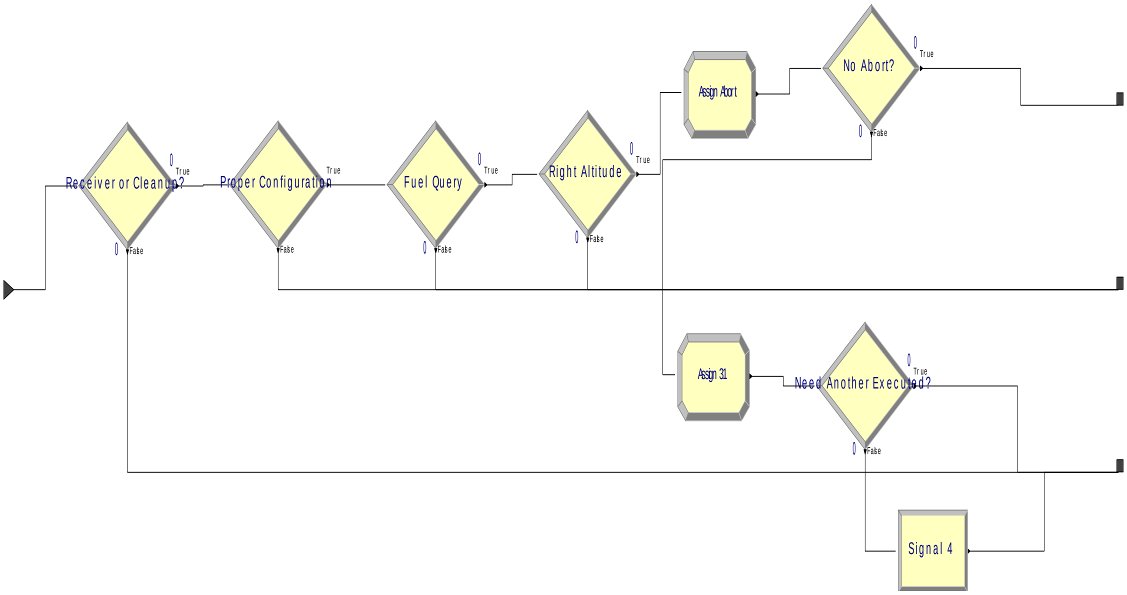


Figure 9: Depiction of Decision Matrix Sub-model

The entities next enter the Decision Matrix sub-model. This sub-model is a series of decide modules that determine if an entity is configured properly, has enough fuel, and does not abort prior to proceeding to refuel the receiver entity. If an entity leaves the flow because of a false condition in any of these modules, the next tanker entity in the Executed Tanker queue will be released to complete the refueling. If there are no executed tanker entities to complete the refueling, another entity is released from the Unexecuted Pool module through the Tanker Control Process or from a signal created in this sub-model. Receiver or Cleanup? determines if the entity is proceeding through the model to be matched with a receiver or is just being removed from the Executed Tanker queue because there are no more receivers. If proceeding to a refueling event, the entities move to the Proper Configuration module. If the entities are just being moved from the queue at the end of the simulation run, they proceed directly to the RTB Process sub-model. Proper Configuration is a decide module that determines if the tanker entity is configured appropriately to refuel the receiver entity in the Match module. It is a 2-way by condition decision. If the condition is true, the entity continues to the Fuel Query module. If the condition is false, the entity proceeds to the Future Need Process sub-model. Fuel Query is a 2-way by condition decision module that determines if the tanker entity has enough fuel to meet the offload requirement for the receiver in the Match module. The expression used also accounts for any fuel burned by the tanker entity while waiting for its next air refueling. Fuel is burned at a rate of 179 pounds per minute (10,718 pounds per hour) in accordance with Air Force Pamphlet 10-1403 planning factors. If the condition is true, the entity continues to the Right Altitude module. This Decide module determines if the tanker's altitude matches the receiver's altitude. If the altitudes do not match, the tanker enters the Future Need Process sub-model. If the altitudes match, the entity next enters the Assign Abort module. This module assigns a new Chance of Abort attribute value to represent the possibility of an airborne abort. A uniform probability distribution between 0 and 1 and the same random number seeds were used as previously to assign the attribute value. The next module is the No Abort? module. The No Abort? module is a 2-way by condition decision module. This module represents an airborne abort and determines if the Chance of Abort is less than the abort rate for the simulation run. No data could be found to give an accurate airborne abort rate for KC-135s. The occurrences of airborne aborts are much rarer than ground aborts, but still must be accounted for. Therefore, it was determined that 0% would be used for simulation runs where the ground abort rate was 0%; and 1% would be used for all other runs. This allows the possibility of an airborne abort to be modeled without allowing the abort rate to become excessive. If the condition is false, the entity is directed to the Assign 31 module, then the Need Another Executed module, and the Signal 4 module before proceeding to the RTB Process sub-model. These modules perform the same functions of assigning the Aborted attribute and signaling to execute another tanker entity if needed as the previously described modules. If the entity does not abort, it exits the Decision Matrix sub-model to the Assign Exit Time module in the Tanker Process sub-model.

The Assign Exit Time module is an assign module that assigns the current time as the attribute Exit Time. This attribute is used to help calculate timing when performing verification analysis on the model. The entities next enter the Match Receiver Data module. This module updates an already assigned attribute and also assigns attributes to the tanker entity, determined by the receiver in the Match module. The following attribute is updated: Fuel (updated to the current state). The attributes Receiver #, AR Start Time, Offload, and AR Time are assigned to equal the receiver in the Match module. This is done for later data collection and verification procedures. These attributes are not updated or assigned prior to this in the sub-model because prior to this point, the entity has not been definitively matched to the receiver. Data Capture 3 is a ReadWrite module that captures data for verification purposes. This module writes the attribute values to the output spreadsheet. The attributes captured are: Tanker #, Receiver #, Configuration, AR Start, Fuel, Offload, AR Time, and Altitude. Upon completing the Tanker Process sub-model, the tanker entities proceed to the Rendezvous Process Sub-model.

Reenter Flow Process Sub-model

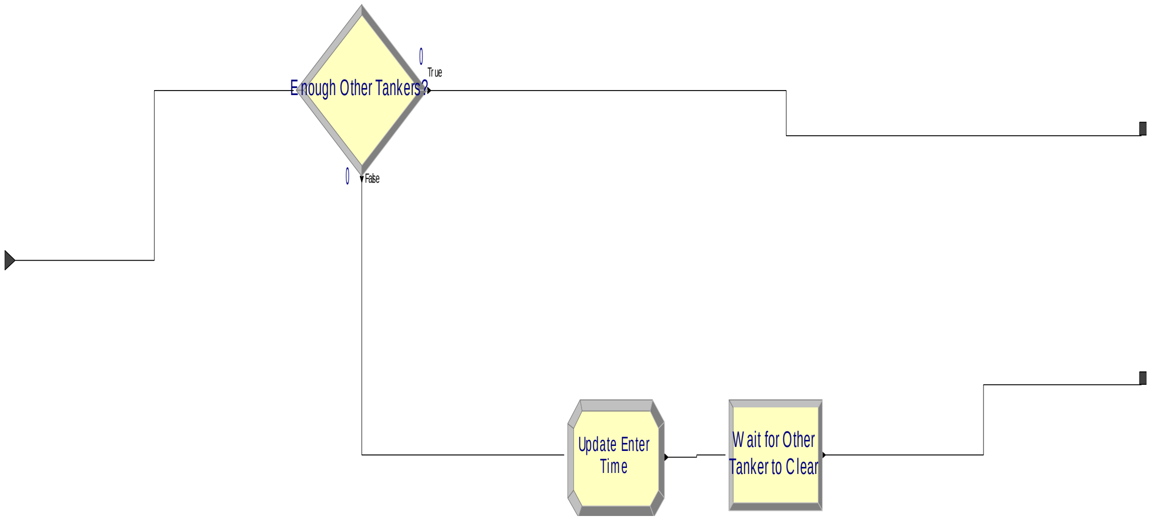


Figure 10: Depiction of Reenter Flow Process Sub-model

The Reenter Flow Process Sub-model serves two purposes. The first purpose is to determine if the entity trying to reenter the executed tanker pool is still needed. The second purpose is to delay its entry until all the model actions occurring at that time are completed before it reenters the pool executed tanker entities. The Enough Other Tankers? module is a 2-way by condition Decide module. It determines if there are already enough executed tankers to match up with the remaining receivers. This allows tanker entities to proceed to the RTB Process sub-model if they are not needed, rather than be left in the Executed Tanker queue. It also ensures a more accurate collection of data for analysis and verification. If a need still exists, the entity proceeds to the Update Enter Time module. The Update Enter Time module is used to update the tanker entity entry time into the Executed tanker pool. This time must be updated to ensure that future decisions involving the entity are based off accurate time representations. The entity then proceeds to the Wait for Other Tanker to Clear module. The Wait For Other Tanker to Clear is a Delay module. Entities are delayed for 1 second in this module. This delay prevents entities that did not meet the needed criteria for the receiver waiting in the Match module from being caught in a continuous loop. The delay allows another executed tanker to be matched with the receiver or new tanker to be executed. Without the delay, the same entity returns to the Executed Tanker queue and prevents a new tanker entity from being executed. The entities are then moved to Executed Tanker Pool module and await their next air refueling tasking.

Rendezvous Process

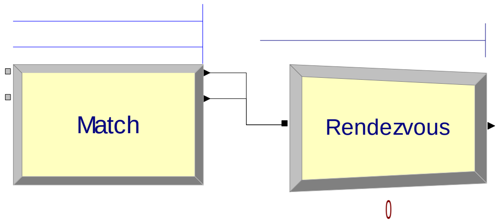


Figure 11: Depiction of the Rendezvous Process Sub-model

The Rendezvous Process Sub-model represents the matching of receiver and tanker entities prior to refueling. The Match module has two queues inside it. One queue is for receivers and the other is for tankers. This allows for only a single receiver and tanker entity to be matched together. This prevents receiver entities with the same AR

Start Time from being batched together for refueling. Once one of each type of entity has entered the module, they are both released to the Rendezvous module. Rendezvous is a batching module. It joins the two entities into a new single entity for refueling. As soon as a batch size of two is formed, the new batched entity is released to the Refueling Process sub-model.

Refueling Process

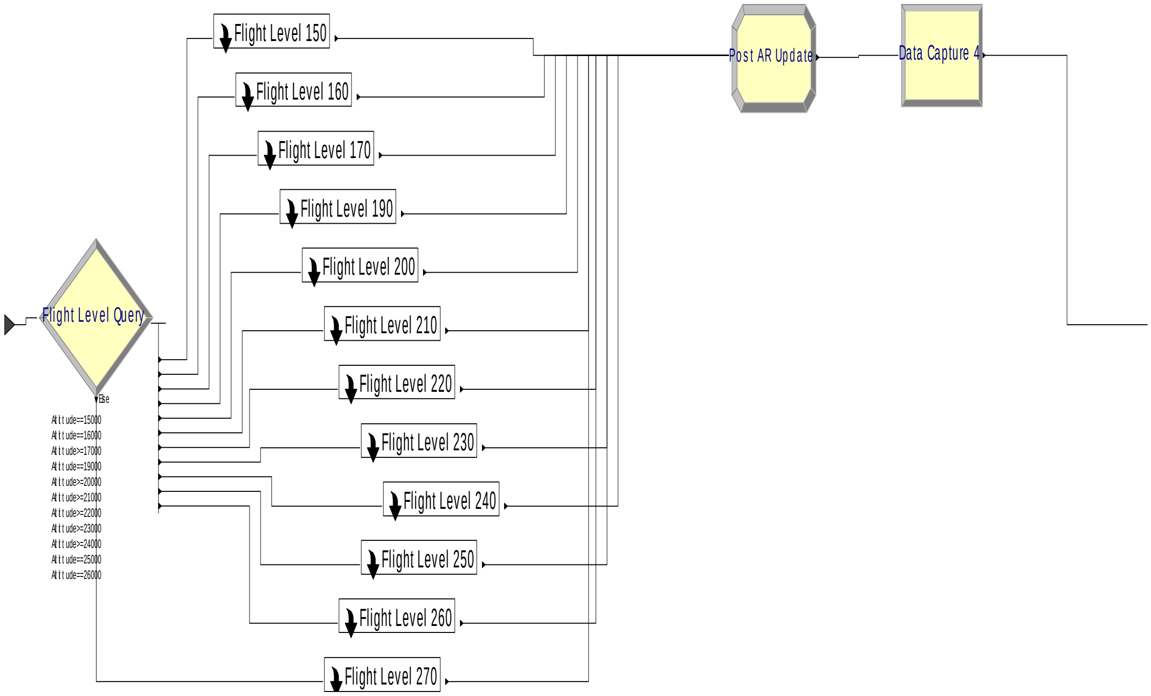


Figure 12: Depiction of the Refueling Process Sub-model

The Refueling Process Sub-model represents the actual air refueling events as they occur. The Flight Level Query module is a 12-way by condition decide model. The decision is determined by the Altitude attribute. This sends the batched entities to their scheduled refueling altitude. Each altitude is represented by a further sub-model. All of the altitudes used in the entire problem set are represented. This allowed the same model to be used for all of the tracks, even if a particular altitude was not tasked for that track. The altitudes covered flight levels 150 to 170 and 190 to 270 (flight level 180 was not used in the problem set for any tracks). The Flight Level Sub-models are detailed below. After completing the Flight Level Sub-model, the separated tanker entities proceed to the Post-AR Update module. This Assign module updates the Fuel attribute and assigns a new attribute, Last AR Time. The Last AR Time attribute denotes the time the entity completed the air refueling and is equal to the current simulation time. The entity then proceeds to the Data Capture 4 module. This is a ReadWrite module that writes to the output spreadsheet for verification purposes. The attributes captured are: Tanker #, Fuel, and Last AR Time. The entities then proceed to the Future Need Process sub-model.

Flight Level Sub-models

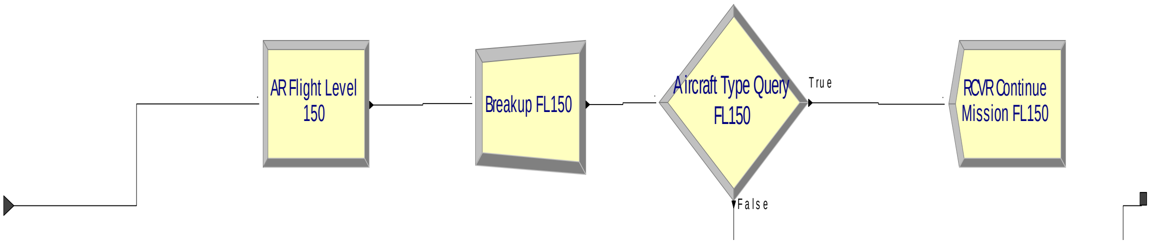


Figure 13: Depiction of Flight Level Sub-model

Each Flight Level Sub-model contains the same modules; with flight level specific names. These sub-models represent the air refueling taking place and the subsequent break-up of the tanker and receiver aircraft to continue their respective missions. The AR Flight Level 150 module is a Process module. The process represented is a delaying action. The duration of the delay is determined by the AR Time attribute. Once the delay for air refueling is complete, the batched entities continue on to the Breakup FL150 module. This Separate module splits up the batch, with each entity retaining their original attribute values. As the entities exit the Breakup FL150 module, they enter the Aircraft Type Query FL150 module. The entities are directed on their path by this 2-way by condition Decide module based on their entity type. Receiver entities advance to the RCVR Continue Mission FL150 module where they are disposed. Tanker entities proceed to the Post AR Update module to continue their mission.

Future Need Processes

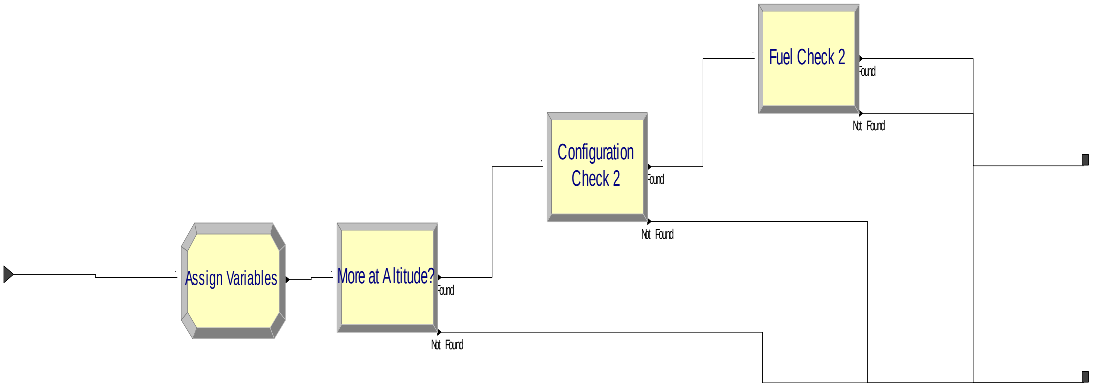


Figure 14: Depiction of Future Need Processes Sub-model

The purpose of the Future Need Process sub-model is to determine if there is a future need for the entities that enters it. The sub-model determines if there are any more receiver entities that match the altitude, configuration, and fuel available of the tanker entity. Entities enter this sub-model from the Refueling Process sub-model and the Tanker Process sub-model. The modules inside these sub-models are the Assign Variables, More at Altitude?, Configuration Check, and Fuel Check. The Assign Variables module is the first module in this sub-model. It matches the tanker’s attribute values for altitude, configuration, and fuel to variables of the same names. Variables are utilized by the Search modules in this sub-model. The entity then continues to the More at Altitude? module. This Search module determines if there are any more receiver entities in the RCVR Wait Until AR Start Time queue that match the altitude of the tanker entity. If no more receivers match the altitude, the tanker moves to the RTB Process sub-model. If there future receiver demands at that altitude, the entity next enters the Configuration Check 2 module. This model searches the RCVR Wait Until AR Start Time queue to determine if any future receivers match the tanker's configuration. Again, if no future need exists, the tanker is sent to the RTB Process sub-model. If a future need is found, the entity proceeds to the Fuel Check 2 module. The Fuel Check 2 module determines if the tanker entity has enough fuel to meet any future receiver demands; adjusted for the fuel that the entity would consume waiting for that air refueling event. If there is a matching receiver, the tanker entity returns Tanker Process sub-model, through the Reenter Flow Process sub-model path. If no match is found, the entity is directed toward the RTB Process sub-model.

RTB Process Sub-Model

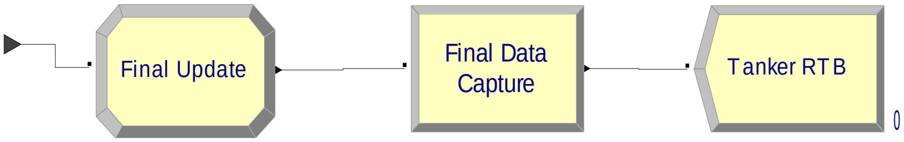


Figure 15: Depiction of the RTB Process Sub-model

The RTB Process is used to finalize the actions of the tanker entities and provides a gathering point for data. It represents the tankers returning to base at the end of their mission. The Final Update module is an Assign module that provides a new attribute, Tanker Flight Duration. The Tanker Start Time is subtracted from the Last AR Time to determine the total number of minutes the entity is in an executed status. This is later added to the enroute time to give the final flight duration for the schedule. Final Data Capture is a ReadWrite module that captures the values of the following attributes: Tanker #, Fuel, Tanker Flight Duration, and Aborted. This is once again for verification purposes, as well as for creating the final schedule. The Tanker RTB module is a Dispose module that allows the entities to be removed from the simulation as their missions are completed.

Treatment 1: Altitude Freedom Introduced

The primary difference in the model for this treatment has to do with assigning a set altitude to tanker entities. The entities are still assigned an attribute value to match their first receiver when they enter the Start Tanker Time module. The first change comes in the Decision Matrix sub-model. Because the tankers can now move freely between altitudes to refuel with any receivers, the Right Altitude module has been removed.

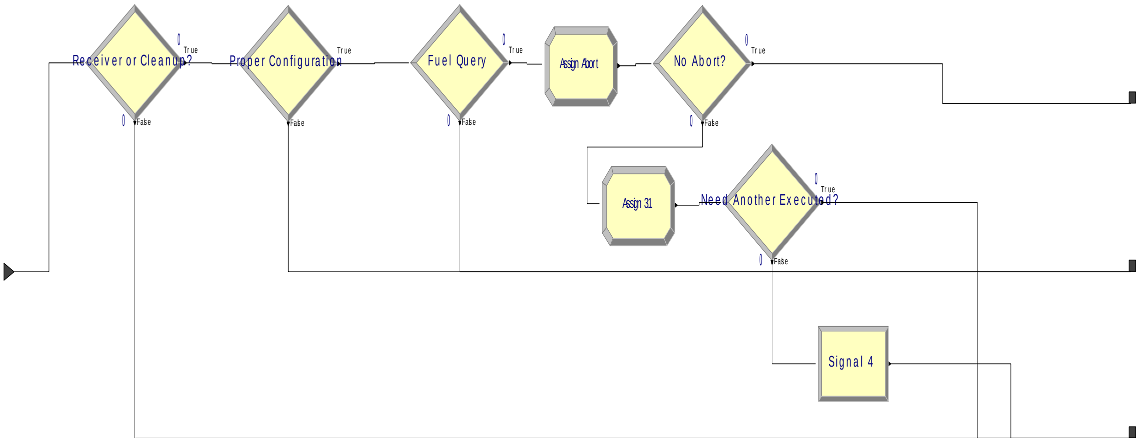


Figure 16: Depiction of the Decision Matrix Sub-model, Treatment 1

The next change for this treatment occurs in the Match Receiver Data module. The Altitude attribute is now matched to the receiver in the Match 1 queue. This allows the tanker's altitude to reflect any changes made after their first refueling event.

The final change in this treatment is in the Future Need Process sub-model. The More at Altitude? module has been removed and the Assign Variables module no longer assigns the Altitude variable. These were no longer necessary because of the altitude restrictions not being present.

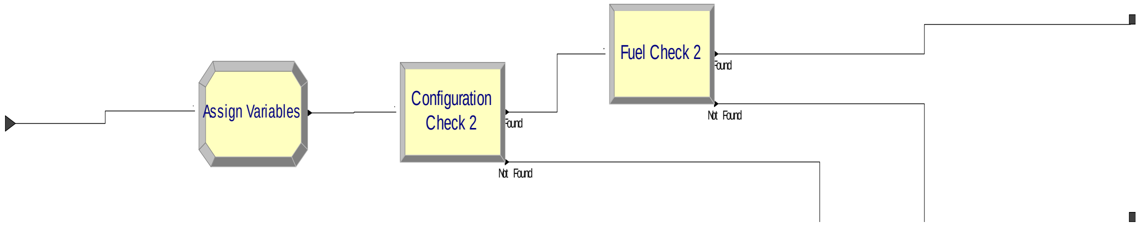


Figure 17: Depiction of Future Need Process Sub-model, Treatment 1

Treatment 2: Introduction of Tanker Consolidation

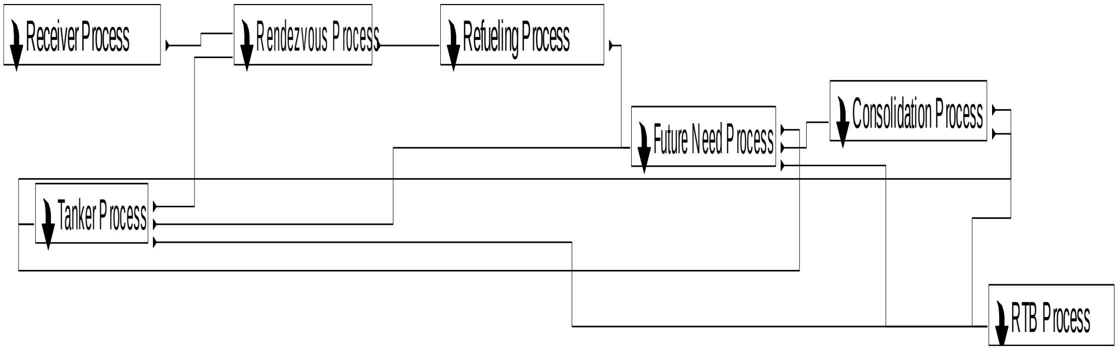


Figure 18: Depiction of Main Model with Tanker Consolidation

The changes for this treatment were imbedded in the previously created Future Need Process Sub-model and the new sub-process, Consolidation Process. These additions control both the decision-making logic for determining if consolidation is possible or necessary and steps for the tanker consolidation itself.

Future Need Process Sub-model Additions

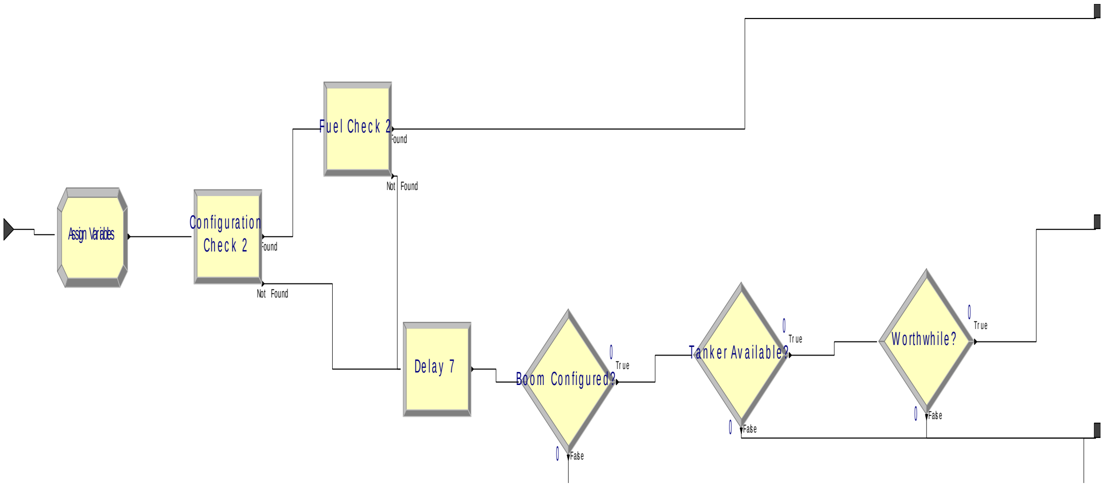


Figure 19: Depiction of Future Need Process Sub-model, Treatment 2

The changes for this sub-model are contained within three Decision modules. These modules encapsulate the decision-making logic that determines if tanker consolidation is feasible. Entities enter from two other sub-models, the Refueling Process and Tanker Process. Entities flowing from the Tanker Process Sub-model were rejected for an air refueling because they lacked the fuel to meet the receiver's demands. They process through this sub-model to determine if there are any future demands that they could meet, and if that is not true, whether consolidation is a possibility. This is necessary because the logic that determines if an entity returns to the Executed Tanker Queue may have been proven false by later occurrences. A future need may be filled by a different tanker entity, therefore negating the need that returned the subject entity to the queue. This allows them to be removed from the pool and the actions necessary to remove the entity from the model to be taken. Entities arriving from the Refueling Process are sorted the same way, but the intention is to determine the future needs and/or actions of the entity at this earlier point in the system. The first two modules perform the same function as they did in Treatment 1, to determine if there is a future need for the entity to fill. If not, the entity is directed towards the consolidation decision-making tree. The first module is the Delay module. This module delays entities for 1 minute. This prevents entities from proceeding through the decision modules and on to the Consolidation Process sub-model prematurely. If the entities are not delayed, they could pull an executed tanker for a consolidation when that tanker should be proceeding to a refueling with a receiver. If there is only one tanker in the queue, an extra tanker may be executed to meet that receiver's demand. The efficiency of the plan would be adversely affected. This allows all of the actions that are supposed to take place during that minute to happen before consolidation is attempted. The Boom Configured? module determines if the tanker entity is configured for boom or probe and drogue refueling. This process determines if an entity can offload fuel, or assume the tanker role, for a consolidation. Therefore, only boom configured entities are eligible for selection. If an entity is configured for probe and drogue, it is directed towards the RTB Process sub-model.

If boom-configured, the entity proceeds to the Tanker Available? decision module. This module determines if there are any executed tanker entities that can be used to match up with for consolidation. Only executed entities are considered because adding another entity to the executed tanker queue would not help the efficiency of the model, one of the primary goals. If there are no tanker entities available for consolidation, the entity is routed to the RTB Process Sub-model.

If a tanker entity is available, the next step is the Worthwhile? decision module. This module determines if the fuel gained by the receiver-tanker is greater than the fuel expended to perform a consolidation event. If the tanker cannot offload more than 20,000 pounds of fuel, then the consolidation is rejected and the entity is directed to the RTB Process Sub-model. This amount was used because it represents the minimum amount of fuel that both entities will burn to complete the consolidation multiplied by two, rounded to the five thousand pound increment.

$$Fuel_{Consol\ Min} = Time_{Consol} * (Fuel\ Burned_{Tanker\ 1} + Fuel\ Burned_{Tanker\ 2})$$

Just gaining an equal amount of capability as the resources expended was not enough to make consolidation worthwhile. This amount covers the quantity of fuel expended by the entities and allows for enough additional fuel to meet a modest receiver demand. The modest receiver demand was determined by taking the average offload (7785 pounds) for receiver demands less than 10,000 pounds. There were 282 receiver requests that included a demand less than 10,000 pounds. This ensures that the additional consolidation fuel could meet the demands of 39% of the possible receiver demands. If a consolidation is determined to be possible, the entity is directed to the Consolidation Process Sub-Model. If not, it is moved to the RTB Process Sub-model.

Consolidation Process Sub-model

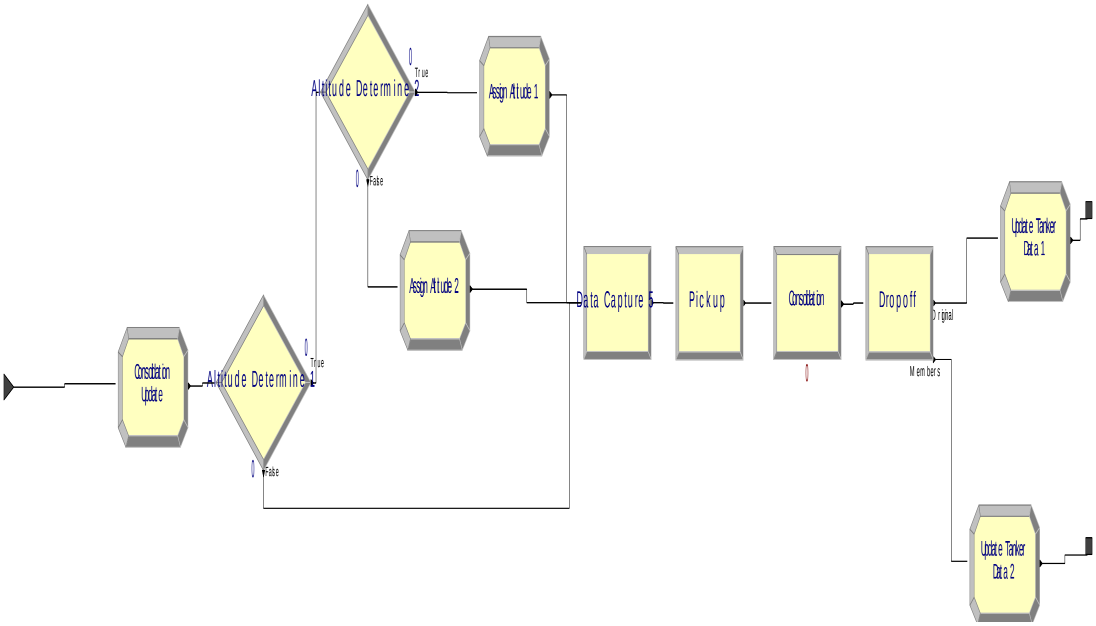


Figure 20: Depiction of Consolidation Process Sub-model

This process sub-model represents the tanker consolidation process. In this process, the tanker entity has its attributes updated, picks up a receiver-tanker, and then both entities are directed on their respective paths in the model. The Consolidation Update module assigns and updates several attributes. The attributes are: Consol Tanker #, Tanker #, Offload Available, Onload Available, AR Start Time, Consolidation Amount, and AR Time. The Consol Tanker # provides the tanker entity offloading fuel a new number that allows it to be identified as a consolidating tanker. The Tanker # is changed to match the number of the first tanker in the Executed Tanker Queue. This is used to identify which entity the consolidation is to be accomplished with. The Offload Available is the tanker's current fuel amount. The Onload Available determines how much fuel the first entity in the Executed Tankers Queue can receive. The AR Start Time utilizes the current simulation time and represents when the consolidation will take place. The Consolidation Amount is the lower value of the tanker's offload available and the receiver-tanker's onload available.

The AR Time is the length of time the consolidation will require. It is determined by selecting the offload available of the tanker entity or the on-load available of the receiver-tanker, whichever is lower. The lower amount will be the limiting factor of the consolidation. Unlike the receiver requests generated in CMARPS, no pre-determined air refueling durations are provided. In order to determine the time required for a consolidation event, calculations were completed on similar airframe data provided by

CMARPS. First, the total refueling time was broken up into two factors: maneuvering time and offload time.

$$T_{Total} = T_{Manuevering} + T_{Offload}$$

To determine offload time, the total offload was divided by the offload rates published in the ATP-56(B) refueling manual (the chart used to determine the rate is included in).

$$T_{Offload} = Q_{Offload}/R_{Offload}$$

The airframes used were: E-3, E-6, E-8, and RC-135. All of these airframes had similar rendezvous speeds, air refueling speeds, and airframe sizes to the KC-135. The maneuvering time consisted of the time required for a receiver to enter the track, rendezvous with the tanker, attain a contact, and maneuver away from the tanker and exit the track. To determine the maneuvering time for each receiver, the offload time was subtracted from the total time.

$$T_{Manuevering} = T_{Total} - (\frac{Q_{Offload}}{R_{Offload}})$$

The mean maneuvering time for each airframe was determined, and then an overall mean was calculated. This mean maneuvering time was 19 minutes.

Once the updates are completed, the altitude that the consolidation will occur at must be determined. Altitude Determine 1 is a Decide module that establishes whether or not there is an air refueling scheduled at the tanker's current altitude during the time that consolidation would occur. If there is no conflict, the tanker’s altitude becomes the consolidation altitude and the entity proceeds to the Data Capture 5 module. If there is a conflict, the entity moves to the Altitude Determine 2 module. This module mirrors the previous one, except that it looks at the receiver-tanker’s altitude for conflicts. If there are no conflicts, the Assign Altitude 1 changes the Altitude attribute to match the receiver-tanker. When a conflict exists, the entity enters the Assign Altitude 2 module and an altitude of 18,000 is assigned. There are no refuelings assigned to this altitude in any of the tracks, therefore it is an option that is always available. This is the last option because it requires two entities to adjust altitudes, rather than one. Once the altitude is assigned, the entity proceeds to the Data Capture 5 module.

The Data Capture 5 module is used to capture data for verification and schedule production purposes. The data collected are: Consol Tanker #, Tanker #, Offload Available, Onload Available, Consolidation Amount, AR Start Time, and AR Time. The entities then advance to the Pickup module.

The Pickup module is used to represent the consolidation rendezvous. The tanker entity reaches back to the Executed Tankers Queue and pulls the first entity to itself. The “picked up” entity then becomes the receiver-tanker. The entities are grouped together and moved on to the Consolidation Module.

The Consolidation Module is a Process module that corresponds to the consolidation event. The process is a standard, delay process that has duration equal to the AR Time. When the consolidation process delay is completed, the entity group moves to the Dropoff module.

The Dropoff module is used to split up the entities from the group. The entities retain their attribute values from before the Pickup Module, except that the receiver-tanker takes the tanker's values for Consolidation Amount, AR Start Time, and AR Time. These values will be used later to update the receiver-tanker's attributes. The tanker next enters the Update Tanker Data 1 module and the receiver-tanker advances to the Update Tanker Data 2 module.

The Update Tanker Data modules adjust the entities' attributes to reflect the changes enacted during the consolidation. The tanker's Tanker #, Last AR Time, and Fuel attributes are updated. The Tanker # is returned to the original Tanker #, as the receiver-tanker's number has already been recorded. The original tanker number is necessary for verification purposes. The Last AR Time is given the current time as its value. The Fuel is updated to account for the fuel offloaded and the fuel burned during the consolidation. The entity then progresses to the RTB Process. The receiver-tanker's Fuel attribute is updated to the amount after consolidation. The entity then is returned to the Tanker Process Sub-model.

Treatment 3 Additional Maneuvering Time Fidelity

The changes made for Treatment 3 center around increasing the time fidelity for maneuvering that a tanker entity may have to perform to join-up with a receiver entity or for a consolidation event. Because the tanker entities cannot move between different tracks, the only maneuvering takes place in the vertical plane. Maneuvering horizontally for a rendezvous within a track is not a factor because when an anchor refueling track is utilized, the tanker continually circles the track and the receivers join on the tanker using airborne controller direction, radar, or visual identification. This horizontal maneuvering timing is accounted for in the air refueling event durations provided by CMARPS and in the calculation of consolidation timing. There are two process sub-models affected by the vertical maneuvering timing adjustment, the Decision Matrix Sub-model and the Consolidation Process Sub-model.

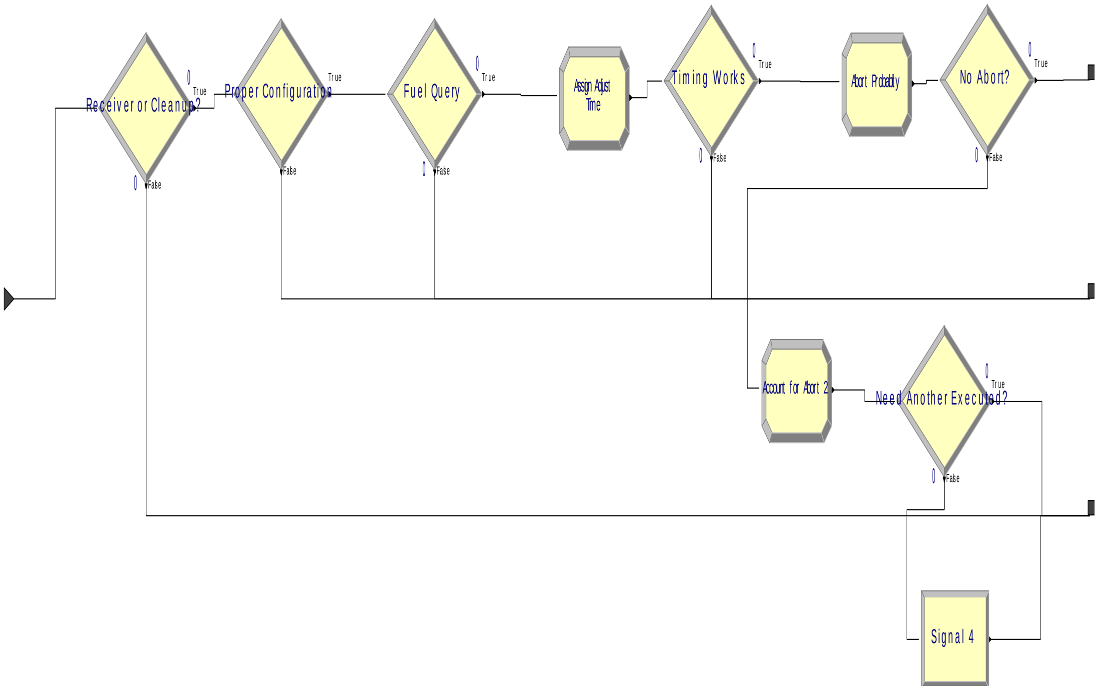


Figure 21: Depiction of Decision Matrix Sub-model, Treatment 3

The change to the Decision Matrix sub-model is contained in the addition of an Assign module and another Decide module. The Assign Adjust Time module assigns an attribute that determines the time required to adjust altitude to match the awaiting receiver's altitude. It adds the tanker entity's Enter Time to the time required for adjusting altitude. The altitude adjustment time is determined by calculating the absolute value of the current altitude minus the receiver's altitude and then dividing by the standard climb or descent rate. A standard climb or descent rate of 1500 feet per minute was used, as that is the default setting in the KC-135s onboard Flight Management System computer (Department of Defense, 2011).

$$T_{AR\ Start\ Time} \geq (abs(A_{Current} - A_{Projected}))/R_{Climb/Descent}$$

The Timing Works? decision module determines if the amount of time required for the tanker to adjust altitude would allow for the refueling to remain feasible. If the tanker entity can adjust altitude prior to the AR Start Time, it continues on to the Abort Probability module. If the timing does not work, the entity is redirected to the Future Need Process sub-model.

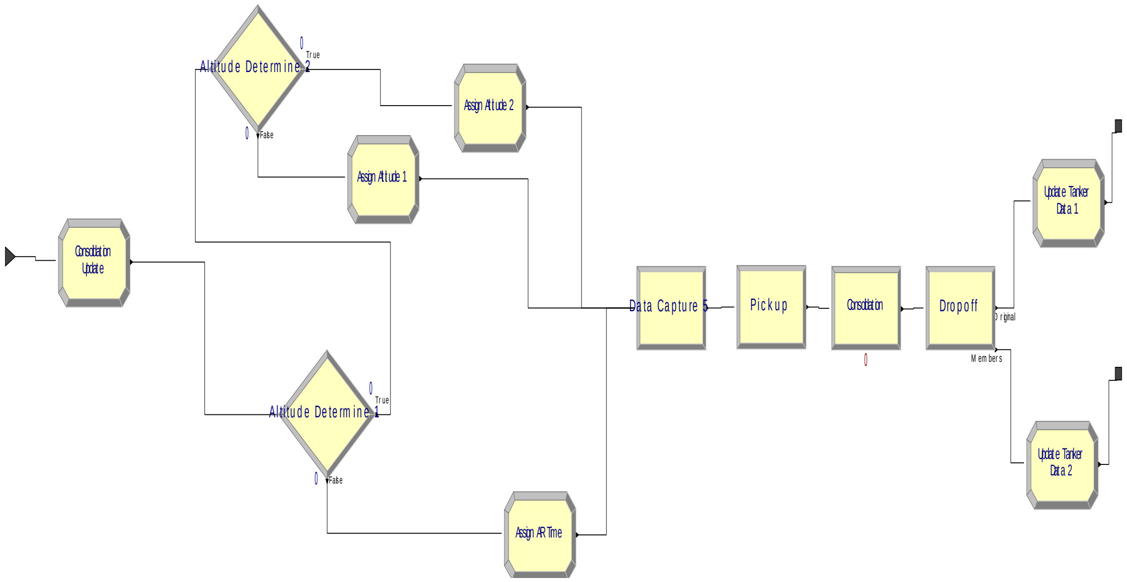


Figure 22: Depiction of the Consolidation Process Sub-model, Treatment 3

The second Process affected in this treatment is the Consolidation Process. The effect is centered on the adjusted AR Start Time. The timing required to adjust altitude by either or both entities causes the AR Start Time to be adjusted. Prior to determining the AR Start Time, an altitude must be determined. Therefore, the altitude determination decision modules were moved in front of the Consolidation Update module for this treatment. The decision expressions were adjusted to account for the maneuvering time when determining which altitude to use for the consolidation. In addition, an Assign AR Time module was added after the Altitude Determine 1 module. This allows the appropriate AR Start Time attribute to be assigned to tankers maintaining their original altitude. The new AR Start Time attributes were included in the Assign Altitude modules if the two other altitudes were utilized. The Assign Altitude 1 used the same expression, just adjusted for using the receiver-tanker altitude. The Assign Altitude 2 module utilizes an expression that looks for the maximum value of either the tanker or receiver-tanker adjustment times. Whichever entity takes longer to adjust altitude determines the earliest time consolidation can begin.

Treatment 4 Crew Duty Day Limitation

As stated previously, one benefit of tanker consolidation is the ability to extend a KC-135s time airborne. If the flight time is extended too long, regulatory limitations may be exceeded. These limitations are put in place for safety, as extended flight time may cause fatigue in crewmembers and lead to a mishap. The KC-135 has an operational crew duty time limitation of 18 hours. Crew duty time is defined as "…that period of time an aircrew may perform combined ground/flight duties" (Department of the Air Force, 2010). The crew duty limitation for the simulation will only include the time that the tanker is on-station in the air refueling track. To ensure that crew duty time limitations are not exceeded, the maximum time on track must be determined for each track. This maximum time on track will be subtracted from the enroute times to and from the track to account for the total flight time. In addition, a standard time allotment for ground activities needed to be determined.

The amount of time required for ground activities varies from base to base. This time starts when either one hour after alert notification or at the time when the first crew member reports for duty. It was determined that the first crew member report time would be used for this simulation due to the fact that a schedule was being built and this would allow the crews to self-alert. The amount of time required from crew report until airborne and from landing until all activities are complete also varies depending on the base of origin. After discussing the matter with the research sponsor, it was decided to use three hours for pre-flight ground time and one hour for post-flight ground time. The three hours represents the normal time that we had both experienced in our 35+ years of combined flying in the KC-135 to report, brief the mission, perform pre-flight checklists, and takeoff. The one hour post flight was determined using the same normal observations. This left 14 hours (840 minutes) for the aircraft to fly to and from the track and remain on-station. The maximum on-station times for each track are listed in Table 3.

Table 3: Track Crew Duty Day Limitations

Track	Time to Track (minutes)	Time From Track (minutes)	Maximum On-Station Time (Minutes)
1	61	35	744
2	70	43	727
3	75	49	716
4	86	59	695
5	65	41	734
6	77	53	710
7	55	34	751
8	55	34	751
9	52	28	760
10	74	51	715
11	74	53	713
12	72	48	720
13	60	37	743
14	67	44	729
15	68	47	725
16	61	43	736
17	72	51	717
18	80	63	697
19	84	64	692
20	67	47	726
21	77	63	700
22	81	67	692
23	94	82	664

The crew duty time limitation is accounted for by checking the elapsed on-station time at three different points in the model. The first point is during the Decision Matrix Process sub-model.

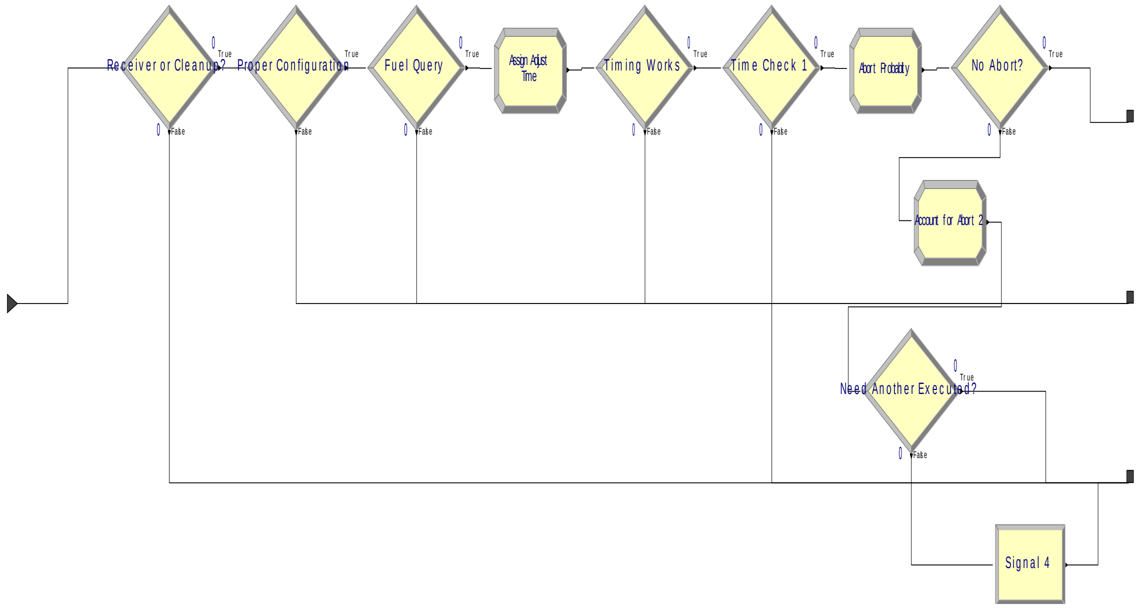


Figure 23: Depiction of the Decision Matrix Process Sub-model, Treatment 4

In this sub-model, a decide module (Time Check 1) was added to determine if the tanker entity will exceed the maximum crew duty day if it performs the next required receiver air refueling. It decides if the time tanker's current flight duration combined with the time required to complete the air refueling event is greater than the track's maximum on-station time.

$$(T_{Now} - T_{Tanker\ Start\ Time}) + T_{AR\ Time} \geq T_{Track\ Maximum}$$

If the entity will not exceed the maximum on-station time, it continues to the Abort Probability module. If the entity will exceed the maximum on-station time, it is directed to the RTB Process. This module is needed in this process because the logic that returned the entity to the process may have previously determined adequate crew duty time, but subsequent events may have rendered that logic false.

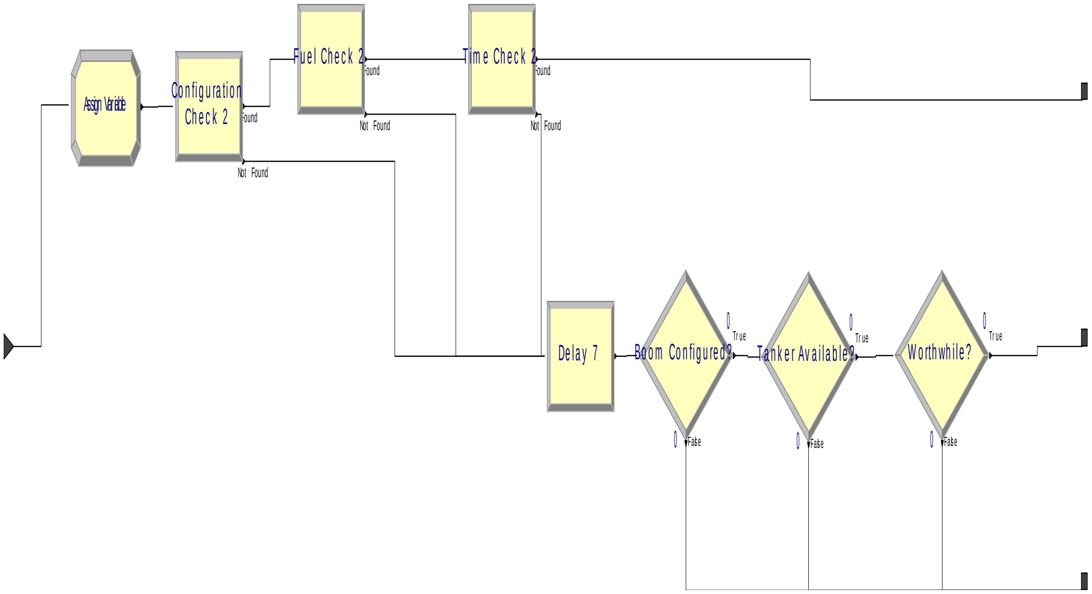


Figure 24: Depiction of the Future Need Sub-model, Treatment 4

The Future Need Sub-model has been changed to include an additional assigned variable and a third Search module, Time Check 2. The Assign Variable module now also assigns the variable Tanker Duration. The Time Check 2 module searches the Receiver Awaiting AR Time Queue to determine if there is a future refueling event that a tanker entity, already determined to have the proper configuration and adequate fuel, can accomplish prior to exceeding the crew duty limitation. If a future event can be completed, the entity is directed to the Tanker Process Sub-model. If there are no future receiver matches, the entity proceeds to the consolidation decision modules and follows the previously described path.

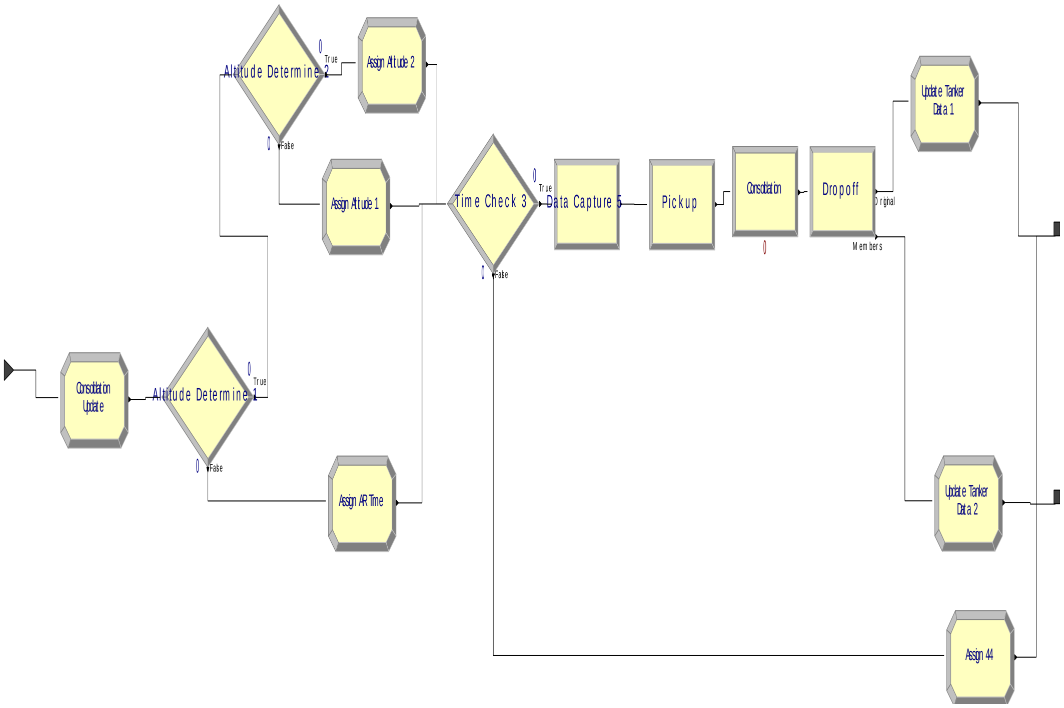


Figure 25: Depiction of the Consolidation Process Sub-model, Treatment 4

The changes to the Consolidation Process Sub-model are contained in the Time Check 3 and Assign 44 modules. The Time Check 3 module mirrors the Time Check 1 decision module in the Tanker Process Sub-model. It determines if accomplishing a tanker consolidation will cause the entity to exceed the track's maximum on-station time limit. If the limit will not be exceed, the entity moves on to the Consolidation Update module. If the limit will be exceeded, the entity is directed to the Assign 44 module. The placement of the module allows the consolidation timing to be determined prior to the decision to consolidate, while not changing any of the attributes that will be collected during the RTB Process if consolidation is not feasible. The Assign 44 module returns the Tanker # back to the original value for verification analysis.

Validation and Verification

As previously noted, validation of models that incorporate functions not found in the real system is difficult. Validation for this model was accomplished through discussion with the research sponsor. All model inputs were either provided by the sponsor, determined through research and approved by the sponsor, or determined through discussion with the sponsor.

Verification was accomplished through many stages of the simulation. For each treatment, the simulation was run and a step-by-step verification was accomplished. This process involved running each model utilizing the Anchor 1 track inputs. Each entity was followed through each step of the model. Each decision made within the model was checked by manually calculating the logic inputs from the output spreadsheet to determine if the entity's decision was correct. If all of the actions were determined to be correct, the model was run for all tracks. During these subsequent runs, further verification was conducted. All probe and drogue entity values were checked to ensure that none of these entities acted as the tanker in a consolidation. Next, all tanker entities that completed a consolidation were checked to ensure that conditions that led them to consolidate were correct. All of the entity's final fuel values were checked to ensure that none finished with a value less than 0. Further, any entities that had final values for fuel quantities of 0 were checked for accuracy. Any entities that were executed and performed only a single air refueling were checked to ensure that another executed tanker could not have performed that event. Finally, all flight durations were checked to determine if any entities exceed the crew duty time limitations.

IV. Results and Analysis

The results obtained from this experiment demonstrate that while tanker consolidation is a useful tool for operational flexibility, it does not greatly affect planning efficiency by itself. All of the hypotheses presented previously are not support with statistical significance. The results are compared using an unpaired sample, two-tailed t test to determine if the differences are statistically significant at the 95% level. All t tests are computed using GraphPad Software's QuickCalcs Online Calculators for Scientists (**http://graphpad.com/quickcalcs/ttest2.cfm**). If the results are not statistically significant, a large sample comparison of means determines the number of replications required to provide statistical significance.

Table 4: Mean Number of Tankers Required

	Abort Rate							
	0%		**5%**		**10%**		**15%**	
Treatment	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**
0	**186**	**0**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
1	162	0	171	2.08	177	3	184	3.21
2	160	0	167	2.65	175	2.52	184	0.58
3	163	0	170	2.52	177	5.13	186	6.24
4	163	0	170	2.52	177	5.13	186	6.24

By first comparing the results of the experiments run with a 0% abort rate, the effects of tanker consolidation and increased time fidelity can be examined. The results show that the largest gain in efficiency comes from removing the altitude restrictions utilized by current planning models. Comparing Treatment 0 to Treatment 1 shows a decrease of 24 aircraft. This is a 12.9% increase in efficiency while still maintaining a resiliency level to meet the demand. Introducing tanker consolidation in Treatment 2 only decreases the number of aircraft required by 2, or 1.2%. Increasing the time fidelity required in Treatments 3 and 4 required 3 additional aircraft. This represents a gain of 1.9% from Treatment 2 and 0.6% from Treatment 1.

Table 5: Results at 0% Abort Rate

0% Abort Rate			
Abort Rate	Mean	Standard Deviation	
Treatment 1	162	0	% Difference
Treatment 2	160	0	1.23
Treatment 2	160	0	% Difference
Treatment 3	163	0	-1.88
Treatment 3	163	0	% Difference
Treatment 4	163	0	0.00
Treatment 0	186	0	% Difference
Treatment 1	162	0	12.90

The results of the tests utilizing a 5% abort rate begin to show how maintaining the resiliency level with an increased risk affects the efficiency of the model. Comparing Treatments 1 and 2 shows that tanker consolidation has an increased effect on efficiency. The savings in aircraft is doubled from the 0% abort rate. The mean number of aircraft required is decreased from 171 (s.d.= 2.08, n =3) to 167 (s.d. = 2.65, n = 3). This shows a 2.3% gain in efficiency. However, results of the t test present a p-value of .109. These results would only be significant with an 89% confidence level or lower. This means that there is a good chance that the difference is primarily due to chance, because of the use of random numbers. Treatments 3 and 4 each have a mean number of aircraft required of 170 (s.d. = 2.52, n = 3). Comparison of with Treatment 2 results in a t-statistic of 1.42 and p-value of .228. This gives a confidence level of 77%.

Table 6: Results at 5% Abort Rate

5% Abort Rate				
Comparison of Treatments	Mean	Standard Deviation	T-Statistic	P-Value
Treatment 1	171	2.08		
Treatment 2	167	2.65	1.71	0.162
Treatment 2	167	2.65		
Treatment 3	170	2.52	1.42	0.228
Treatment 3	170	2.52		
Treatment 4	170	2.52	0.00	1
T-Statistic: 4 Degrees of Freedom, 95% Confidence Level				

As the abort rate is increased to 10%, the greater risk continues to decrease the efficiency required to maintain resiliency. The mean number of aircraft required in Treatment 1 rises to 177 (s.d. = 3, n = 3). Treatment 2 results in a mean number of aircraft required of 175 (s.d. = 2.52, n = 3). The t test produces a t-statistic of 0.88 with a p-value of 0.427. Comparison of Treatments 3 and 4 to 2 presents a t-statistic of 0.61 and p-value of 0.577. Both of these results on give a confidence level around 50%.

Table 7: Results at 10% Abort Rate

10% Abort Rate				
Comparison of Treatments	Mean	Standard Deviation	T-Statistic	P-Value
Treatment 1	177	3		
Treatment 2	175	2.52	0.88	0.427
Treatment 2	175	2.52		
Treatment 3	177	5.13	0.61	0.577
Treatment 3	177	5.13		
Treatment 4	177	5.13	0.00	1
T-Statistic: 4 Degrees of Freedom, 95% Confidence Level				

The 15% abort rate results again show a very low confidence levels in the differences between the treatments. However, when comparing the results from the 15% abort rate to the results of the 0% abort rate, the effect of maintaining the resiliency rate come further into focus. Comparing Treatment 1 results shows a mean increase of aircraft of 22 aircraft (13.6%). This results in a t-statistic of 11.87 and a p-value of 0.0003. This gives an extremely high confidence level of 99.97%.

Table 8: Results at 15% Abort Rate

15% Abort Rate				
Comparison of Treatments	Mean	Standard Deviation	T-Statistic	P-Value
Treatment 1	184	3.21		
Treatment 2	183	0.58	0.53	0.624
Treatment 2	183	0.58		
Treatment 3	186	6.24	0.83	0.454
Treatment 3	186	6.24		
Treatment 4	186	6.24	0.00	1
T-Statistic: 4 Degrees of Freedom, 95% Confidence Level				

Hypothesis 1 states that incorporating tanker consolidation into planning will increase the efficiency of tanker utilization. To test this hypothesis, Treatments 1 and 2 are compared. The only result that can be deemed statistically significant comes from the tests utilizing a 0% abort rate. This decreases the aircraft required by 1.23%. None of the tests that incorporated randomness show a difference that is statistically significant. One of the focuses of this experiment is the effect the increase in efficiency has on the resiliency of the model. This can only be tested by incorporating risk in the model. The 5-15% abort rates represented that risk. To prove statistical significance, the number of replications required to be run for each abort rate are:

- 5% abort rate: 115

- 10% abort rate: 169
- 15% abort rate: 7388

These large numbers of replications required are infeasible to run for the purpose of this study. Therefore, the results do not support this hypothesis.

Hypothesis 2 asserts that as time fidelity is increased in the model, the efficiency will decrease. The first step in increasing the time fidelity is in Treatment 3, then further in Treatment 4. This hypothesis can be tested by comparing Treatments 2, 3, and 4. Again, the 0% abort rate results show this to be true at a small percentage (1.88%). The introduction of risk leads to a lack of statistical difference in the results though. Further, the results of Treatment 4 are exactly the same as Treatment 3. This is due to the fact that none of the tankers in the model approached the crew duty day limitation of 840 minutes. The longest sortie duration result is 703 minutes. The number of replications required to provide statistical significance at the 95% level are:

- 5% abort rate: 32
- 10% abort rate: 690
- 15% abort rate: 517

Again, the number of replications required is infeasible. The hypothesis is not supported by these results.

The assertion of Hypothesis 3 is that maintaining a desired level of resilience, while increasing risk, will decrease the efficiency of the model. The mean increase in the number of aircraft at each level of increased risk (example: Treatment 1 0% to 5%, 5% to 10%, etc.) is 7.7 (s.d. = 1.07, n =12). This is a mean increase of 4.5% (s.d. = 0.6%, n = 12).

Table 9 shows that these differences are statistically significant at the 95% level in almost all of the comparisons. The overall experimental error is also shown by the P-values in the table. The only exceptions are for Treatments 3 and 4 comparing the 5% to 10% and 10% to 15%. In both cases, the high standard deviation is causing the confidence level to remain below 95%. This hypothesis is partially supported at the 95% confidence level.

Table 9: Comparison of Increasing Abort Rates

	Abort Rate					
	0%		5%			
Treatment	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**T-Statistic**	**P-Value**
1	162	0	171	2.08	7.49	0.0017
2	160	0	167	2.65	4.58	0.01
3	163	0	170	2.52	4.81	0.0086
4	163	0	170	2.52	4.81	0.0086
	5%		**10%**			
Treatment	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**T-Statistic**	**P-Value**
1	171	2.08	177	3	2.85	0.047
2	167	2.65	175	2.52	3.79	0.019
3	170	2.52	177	5.13	2.12	0.101
4	170	2.52	177	5.13	2.12	0.101
	10%		**15%**			
Treatment	**Mean**	**Standard Deviation**	**Mean**	**Standard Deviation**	**T-Statistic**	**P-Value**
1	177	3	184	3.21	2.76	0.051
2	175	2.52	184	0.58	6.03	0.0004
3	177	5.13	186	6.24	1.93	0.129
4	177	5.13	186	6.24	1.93	0.129
T-Statistic: 4 Degrees of Freedom, 95% Confidence Level						

V. Conclusions

The results of this experiment may be useful in several ways for decision makers in the future. The limitations inherent in this study must be acknowledged when using these results for making strategic or operational decisions. This research has also brought to light many opportunities for both follow-on research and new research ideas.

Future Employment of Research Results

This study can provide guidance for leaders in both operational and strategic areas. First, this study shows that tanker consolidation demonstrates great benefits during the execution of an ATO, the effects on planning are minimal at best. Isherwood's 2007 study examined the results of tanker consolidation using post-mission data. The 20% decrease in the number of missions proposed cannot be applied to planning. During mission execution, opportunities for tanker consolidation may be more prevalent because of receiver cancelations and receivers not needing all of the fuel they requested. The receivers make their requests based on their worst-case scenario. Many times that scenario does not occur and the receiver's actual demands are greatly decreased. This allows airborne controllers a great deal of flexibility to manage the efficiency of the tankers by shifting additional receivers to take the extra fuel from the airborne tankers. This begins a "snowball" effect that has tankers who get airborne earlier rolling to later air refueling times. By pushing back the times when new tankers need to arrive in the air refueling tracks, the number of tankers is eventually decreased as the later scheduled tankers stay on the ground due to a lack of requirements. Another option is for the airborne tankers to consolidate their excess fuel into one or more other tankers, which can then meet the receiver requirements later in the day. This again can reduce the number of tankers that actually get airborne and provide air refueling. However, from a planning perspective this increase in efficiency does not hold up. The same number of aircraft still must be made available to meet the needs given in the receivers' requested demands. The decreased actual offload amounts are not guaranteed. If this is included in the plan, there will not be enough fuel available on days when the receivers require all of the planned fuel.

Another reason why tanker consolidation does not affect the planned number of tankers at nearly the 20% rate is that in the models used for planning, the tanker entities generally optimize their utility and continue providing fuel to receivers until they reach their minimum fuel levels or run out of receivers. The mean number of aircraft that consolidated fuel for all tests that included consolidation is 8.33 (s.d. = .048, n = 36). The mean number of aircraft required for these same tests is 173 (s.d. = 9.03, n = 36). On average, only about 4.8% of the aircraft are consolidating fuel. The average amount of fuel consolidated for all tracks per simulation run was only 235,000 pounds. This is just slightly more than one aircraft's fuel load.

One of the limitations to KC-135 efficiency has always been that only receiver can be refueled at a time. In many cases, several different flights of multiple receivers need to refuel at the same time to meet their mission requirements. This requires multiple tanker aircraft be available to refuel with them. Many of the solutions provided during this experiment have the simulation being completed with multiple tankers ending their missions with a large of amount of fuel still available. The primary reason for this is that multiple tankers were required at the same time to meet the receiver needs. The airborne tankers had plenty of fuel to meet the requirements, but were occupied with other receivers.

The appropriate retirement rate of the KC-135 as the KC-46 enters service is the primary strategic use for these results. The ability to quantify the effects of the ability of the KC-46 to consolidate fuel will help ensure that refueling capabilities will still be adequate to support future missions. Based on the results of this experiment, fuel consolidation does not affect the number of aircraft required to meet planning requirements in a significant manner. Including tanker consolidation as a factor in determining a comparison ratio of KC-46 to KC-135 aircraft could cause the KC-135 to be retired at a rate that would significantly undermine the USAF's ability to meet mission requirements.

Limitations and Opportunities for Future Research

Any use of the results of this experiment for future decision making must do so with the acknowledgement of the limitations of this study. The first limitation is that this study was completed using KC-135 data. To accurately determine the effects of tanker consolidation on KC-46 operations, KC-46 data must be used. With the source selection for producing the KC-46 happening so recently, testing of the aircraft has not yet been completed to provide this data. The use of actual KC-46 data may have effects on the results of the experiment that are not readily apparent at this time. When aircraft testing is completed, a study should be completed with the appropriate data substituted in for the KC-46.

The next limitation of this study is that the fuel burn calculations were based on planning figures. Utilizing flight planning software will further increase the fidelity of the model and provide more accurate fuel figures. Flight planning software will recognize the different fuel burn rates at different altitudes and speeds. CMARPS has flight planning software embedded in its model, therefore the inclusion in future research would also allow better use of the current planning models for validation.

The abort rates used are another limitation in this model. Ground aborts can have a variety of causes, but were grouped together for this study. Air aborts were included, but only studied at a standard rate because of the lack of data to determine the actual rate. This lack of fidelity in the abort rates could have affected the outcome of the simulation. Future studies should separate the various causes of ground aborts. The appropriate rates should be determined and utilized for all aborts, air and ground. If no data on air aborts is currently being collected, the collection and analysis of this data could be the subject of a future study. This increase in fidelity will also lead to increased validation of the model.

The short duration of the simulation run limited the utility of the results of the experiment. As previously mentioned, many of the simulation runs ended with several aircraft having large amounts of fuel available for future refueling events. In reality, many of these missions would have carried on into the next day of the operation and refueled more receivers. This would have decreased the number of new tanker aircraft required to meet the next day's requirements. If the first day's requirements were the largest, this would not decrease the number of aircraft needed for the operation. The maximum needed for any day would still be the determinant of the number needed to be available. However, if the requirements increased after the first day, the rollover in aircraft savings could provide a greater efficiency later in the operation. Multiple days may also have presented more opportunities for consolidation. If several aircraft have completed one day's requirements with an abundance of fuel still available, the time gaps between the last refueling on that day and the first on the next day may lead to more consolidations. Future studies should extend the time period covered by the simulation into multiple days.

This study focused on operations from only one tanker base of origin. Studying the other bases will increase the fidelity of the model as well. The base studied, KA04, was geographically close to the refueling tracks and allowed the tankers to take off with the maximum fuel load of 200,000 pounds. The effects of launching tankers from bases that are further removed from the tracks or limit the takeoff fuel weight could change the results of the model. Having tankers from multiple bases utilizing the tracks at the same time could either increase or limit the number of consolidations and their effect on the total number of aircraft required. There were instances where a tanker had fuel available to consolidate, but there were no other tankers available to offload it to. Increasing the number of aircraft utilizing the tracks could also decrease the number of consolidations because all of the available altitudes may be occupied with other refueling events as well.

Further examination of these possible effects is necessary to provide more accurate data for consideration.

A further limitation apparent in this study is the lack of accounting for the "turning" of aircraft. Turning an aircraft is the ability to perform post-flight maintenance checks, refuel the aircraft, and perform pre-flight maintenance checks on an aircraft and get it back in the air for another mission in a minimum amount of time. The ability to turn an aircraft allows that aircraft to fly multiple missions on the same day. This decreases the number of aircraft needed to meet the mission requirements. Future research should include this capability in the model and determine its effects on the efficiency of tanker operations. When the turn time is determined for the KC-46, this should be included in the study as well.

Another area requiring further study is the effect that the KC-46's ability to refuel both boom and probe and drogue receivers on the same mission has on the number of aircraft required. This increased capability must also be quantified to determine if this effect should be included in calculation a substitution ratio of KC-46 to KC-135 aircraft. In this study, there were several probe and drogue equipped tankers that completed their missions with excess fuel because there were no future probe and drogue receiver requirements. The ability to refuel both types of receivers would have allowed them to offload more of their fuel to boom receivers. This could decrease the number of aircraft required to complete the operation.

The tanker consolidation decision logic should also receiver further examination. The tankers in this model had the tendency to continue refueling until they could no longer meet any future receiver needs. In some cases, the aircraft stayed airborne and waited for another receiver for long periods of time. It may be more sensible to consolidate fuel and return the aircraft to its base of origin and allow the aircraft to be turned for another mission. This would save the fuel from being burned by the tanker without having any refueling activity. Even if the other tanker did not have any receiver requirements during that period, it would reduce the fuel burned orbiting in the anchor by close to half. The inclusion of logic that compares the benefits of staying airborne against the benefits of consolidation could lead to more consolidations and a decrease in the total fuel usage. The savings in fuel could come at a cost of additional aircraft required to meet the requirements, however.

The inability of tankers to transition between tracks on the same mission requires further study as well. If studies can show that this restriction has significant effects on the number of aircraft required to meet mission needs, there may be more benefit in planning to allow aircraft to maneuver between several tracks. Currently this is not done because of concerns with airspace deconfliction. If the cost benefits are great enough, the additional burden of planning the deconfliction may be worthwhile.

In the current economic realities being faced by today's military any ability to reduce costs should be examined. Linck's study assumed that the receivers would alter their timing to accommodate the needs of the tanker. As previously stated, that does not align with the current ATO planning process. However, if a future study determined that this would greatly increase cost savings, then the ATO planning process should be examined to determine which method has the lowest total cost. Besides the financial cost, the cost of adjusting refueling times on the receivers' mission must also be determined. In addition, the number of KC-46 aircraft contracted for purchase is not meant to replace all of the KC-135s. There are plans for future tanker purchases to recapitalize the entire fleet. With the economic limitations of today and problems faced during the KC-46 acquisition process, these future purchases may face delays and shortages. The ability of the KC-135 to continue to meet mission requirements at current rates may not hold up as long as it is currently planned to. This could lead to a decrease in the number of tanker aircraft available, and receivers will need to find ways to adjust to this reduced capability. Examining the costs and benefits of receivers adjusting their refueling times to accommodate tanker needs may prepare the USAF for future limitations.

Appendix 1

Sample CMARPS Schedule for Anchor 04

Callsign	Configuration	T/O Time	Land Time	Altitude	AR Start Time	AR End Time	Receiver Request #	Receiver Type	# of Receivers	Offload
Tanker 4-1	Drogue	273	500	22000	359	373	618	F18	2	13600
				22000	425	439	619	F18	2	13600
	Flight Duration	227						Total	4	27200
Tanker 4-2	Boom	597	908	25000	683	747	620	F16C	6	28800
				25000	785	797	621	F16C	2	9600
				25000	835	847	622	F16C	2	9600
	Flight Duration	311						Total	10	48000
Tanker 4-3	Boom	634	921	26000	720	744	630	FA22	4	38600
				26000	847	860	631	F15A	2	17900
	Flight Duration	287						Total	6	56500
Tanker 4-4	Boom	738	1080	19000	824	836	606	F16C	2	8300
				19000	873	943	607	F16C	8	34200
				19000	961	973	608	F16C	2	8900
				19000	1007	1019	609	F16C	2	8900
	Flight Duration	342						Total	14	60300
Tanker 4-5	Boom	762	1166	27000	848	861	638	FA22	2	17000
				27000	929	943	639	FA22	2	19700
				27000	967	978	640	F16C	2	6600
				27000	1001	1033	641	FA22	4	39400
				27000	1091	1105	642	FA22	2	19700
	Flight Duration	404						Total	12	102400
Tanker 4-6	Boom	783	1075	20000	869	918	613	F16C	6	25600
				20000	949	961	614	F16C	2	9300
				20000	1002	1114	615	F16C	2	9000
	Flight Duration	292						Total	10	43900
Tanker 4-7	Boom	807	1058	25000	893	925	623	FA22	4	39500
				25000	929	942	624	F15A	2	17900
				25000	948	997	625	FA22	6	59200
	Flight Duration	251						Total	12	116600
Tanker 4-8	Boom	841	1230	26000	927	940	632	FA22	2	17000
				26000	977	988	633	F16C	2	6600
				26000	1005	1018	634	FA22	2	17000
				26000	1048	1059	635	F16C	2	6600
				26000	1083	1096	636	FA22	2	17000
				26000	1156	1169	637	FA22	2	15700
	Flight Duration	389						Total	12	79900
Tanker 4-9	Boom	868	1085	21000	954	966	616	F16C	2	9000
				21000	996	1025	617	F16C	4	19000
	Flight Duration	217						Total	6	28000
Tanker 4-10	Boom	925	1148	25000	1011	1024	626	F15A	2	17900
				25000	1038	1087	627	FA22	6	59200
	Flight Duration	223						Total	8	77100
Tanker 4-11	Boom	1007	1222	25000	1093	1106	628	F15A	2	17900
				25000	1009	1161	629	FA22	6	59100
	Flight Duration	215						Total	8	77000
Tanker 4-12	Boom	1119	1409	19000	1205	1218	610	F15E	2	19800
				19000	1270	1283	611	F15E	2	19800
				19000	1335	1348	612	F15E	2	19800
	Flight Duration	290						Total	6	59400

Appendix 2

Sample Schedule for Anchor 04, Treatment 2, Replication 1

Callsign	Configuration	T/O Time	Land Time	Altitude	AR Start Time	AR End Time	Receiver Request #	Receiver Type	# of Receivers	Offload
Tanker 4-1	Drogue	273	488	22000	359	373	618	F18	2	13600
				22000	425	439	619	F18	2	13600
	Flight Duration	215						Total	4	27200
Tanker 4-2	Boom	597	1073	25000	683	747	620	F16C	6	28800
				19000	824	836	606	F16C	2	8300
				26000	847	860	631	F15A	2	17900
				20000	869	918	613	F16C	6	25600
				26000	927	940	632	FA22	2	17000
				19000	961	973	608	F16C	2	8900
				20000	1002	1014	615	F16C	2	9000
	Flight Duration	476						Total	22	115500
Tanker 4-3	Boom	634	1037	26000	630	720	744	FA22	4	38600
				25000	621	785	797	F16C	2	9600
				25000	622	835	847	F16C	2	9600
				27000	638	848	861	FA22	2	17000
				19000	607	873	943	F16C	8	34200
				20000	614	949	961	F16C	2	9300
				27000	640	967	978	F16C	2	6600
	Flight Duration	403						Total	22	124900
Tanker 4-4	Boom	807	1188	25000	623	893	925	FA22	4	39500
				27000	639	929	943	FA22	2	19200
				21000	616	954	966	F16C	2	9000
				26000	633	977	988	F16C	2	6600
				21000	617	996	1020	F16C	4	19000
				27000	642	1091	1105	FA22	2	14700
			Consolidation	27000	Tanker 4-8	1106	1129	KC-135	1	17435
	Flight Duration	381						Total	17	125435
Tanker 4-5	Boom			Ground Abort						
	Flight Duration	0						Total	0	0
Tanker 4-6	Boom	843	1165	25000	624	929	942	F15A	2	17900
				25000	625	948	997	FA22	6	59200
				27000	641	1001	1033	FA22	4	39400
				25000	628	1093	1106	F15A	2	17900
	Flight Duration	322						Total	14	134400
Tanker 4-7	Boom	919	1220	26000	634	1005	1018	FA22	2	17000
				25000	627	1038	1087	FA22	6	59200
				25000	629	1109	1161	FA22	6	59100
	Flight Duration	301						Total	14	135300
Tanker 4-8	Boom	921	1407	19000	609	1007	1019	F16C	2	8900
				26000	635	1048	1059	F16C	2	6600
			Consolidation	27000	N/A	1106	1129	N/A	N/A	17435
				26000	610	1205	1218	F15E	2	19800
				19000	612	1335	1348	F15E	2	19800
	Flight Duration	486						Total	8	55100
Tanker 4-9	Boom	925	1342	25000	626	1011	1020	F15A	2	17900
				26000	636	1083	1096	FA22	2	17000
				26000	637	1156	1169	FA22	2	15700
				19000	611	1270	1283	F15E	2	19800
	Flight Duration	417						Total	8	70400

Appendix 3

Input Spreadsheet Example

Rec Cont Input	**Tanker Cont Input**	**Receiver Data Input**						**Initial Tanker Data Input**
AR Start Time	AR Start Time	Receiver #	AR Start Time	Offload	AR Time	Altitude	Configuration	Tanker #

Appendix 4

Output Spreadsheet Example

Initial Tanker Data Capture				Executed Tanker Data Capture								Consolidation Capture						
Tanker #	Tanker Start Time	Configuration	Chance of Abort	Tanker #	Receiver #	Configuration	AR Start Time	Fuel	Offload	AR Time	Altitude	Receiver #	Tanker #	Offload Available	Onload Available	Consolidation Amount	AR Start Time	AR Time

Post AR Data Capture			Final Data Capture			
Tanker #	Offload Available	Last AR Time	Tanker #	Fuel	Total Flight Duration	Aborted

Appendix 5

Formula Used to Determine Number of Replications Required for Statistical Significance

$$R = \left(\frac{S_D}{se(\widehat{\theta}_1 - \widehat{\theta}_2)}\right)^2$$

Where:

R= Number of replications required for statistical significance

S_D= Standard deviation

$se(\widehat{\theta}_1 - \widehat{\theta}_2)$= Standard error in the difference of means

$$S_D = \sqrt{1/(R-1) * \sum_{r=1}^{R} (D_r - \widehat{D})^2}$$

Where:

S_D= Standard deviation

R= Number of replications run

D_r= Difference between sample 1 and sample 2 for each replication

$\widehat{D}$= Mean differences between samples in all replications

$$se\,(\widehat{\theta}_1 - \widehat{\theta}_2) = S_D/\sqrt{R}$$

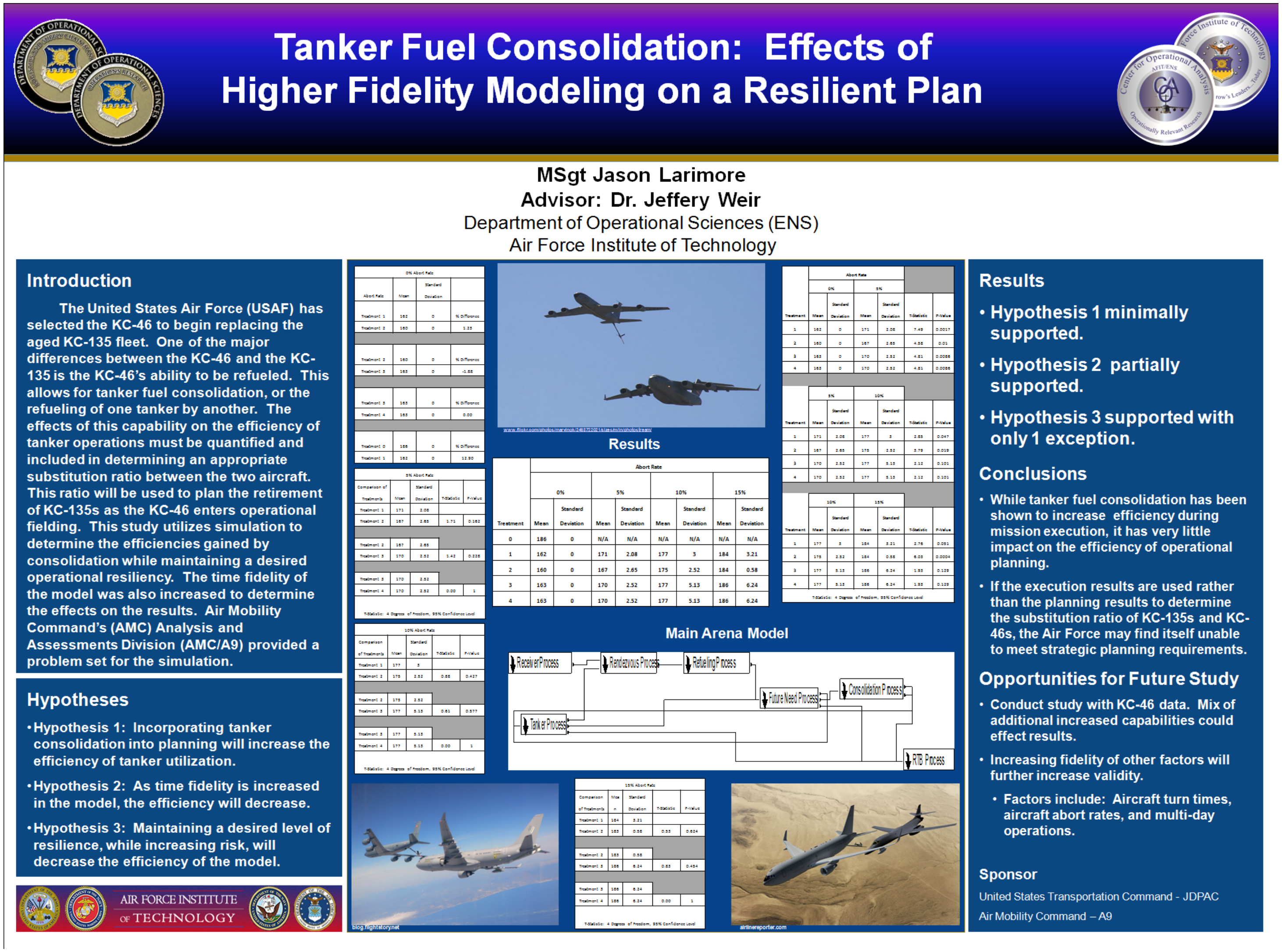
Where:

$se(\overline{\hat{\theta}_1} - \overline{\hat{\theta}_2})$= Standard error in the difference of means

S_D= Standard deviation

R= Number of replications run

Appendix 6



Tanker Fuel Consolidation: Effects of Higher Fidelity Modeling on a Resilient Plan

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Introduction

The United States Air Force (USAF) has selected the KC-46 to begin replacing the aged KC-135 fleet. One of the major differences between the KC-46 and the KC-135 is the KC-46's ability to be refueled. This allows for tanker fuel consolidation, or the refueling of one tanker by another. The effects of this capability on the efficiency of tanker operations must be quantified and included in determining an appropriate substitution ratio between the two aircraft. This ratio will be used to plan the retirement of KC-135s as the KC-46 enters operational fielding. This study utilizes simulation to determine the efficiencies gained by consolidation while maintaining a desired operational resiliency. The time fidelity of the model was also increased to determine the effects on the results. Air Mobility Command's (AMC) Analysis and Assessments Division (AMC/A9) provided a problem set for the simulation.

Hypotheses

- Hypothesis 1: Incorporating tanker consolidation into planning will increase the efficiency of tanker utilization.
- Hypothesis 2: As time fidelity is increased in the model, the efficiency will decrease.
- Hypothesis 3: Maintaining a desired level of resilience, while increasing risk, will decrease the efficiency of the model.

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0% Abort Rate

Abort Rate	Mean	Standard Deviation	
Treatment 1	162	0	% Difference
Treatment 2	160	0	1.25
Treatment 2	160	0	% Difference
Treatment 3	163	0	-1.88
Treatment 3	163	0	% Difference
Treatment 4	163	0	0.00
Treatment 0	186	0	% Difference
Treatment 1	162	0	12.90

5% Abort Rate

Comparison of Treatments	Mean	Standard Deviation	T-Statistic	P-Value
Treatment 1	171	2.08		
Treatment 2	167	2.65	1.71	0.162
Treatment 2	167	2.65		
Treatment 3	170	2.52	1.42	0.228
Treatment 3	170	2.52		
Treatment 4	170	2.52	0.00	1

T-Statistic: 4 Degrees of Freedom, 95% Confidence Level

10% Abort Rate

Comparison of Treatments	Mean	Standard Deviation	T-Statistic	P-Value
Treatment 1	177	3		
Treatment 2	175	2.52	0.88	0.427
Treatment 2	175	2.52		
Treatment 3	177	5.13	0.61	0.577
Treatment 3	177	5.13		
Treatment 4	177	5.13	0.00	1

T-Statistic: 4 Degrees of Freedom, 95% Confidence Level

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Results

Treatment	Abort Rate							
	0%		5%		10%		15%	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
0	186	0	N/A	N/A	N/A	N/A	N/A	N/A
1	162	0	171	2.08	177	3	184	3.21
2	160	0	167	2.65	175	2.52	184	0.58
3	163	0	170	2.52	177	5.13	186	6.24
4	163	0	170	2.52	177	5.13	186	6.24

Treatment	Abort Rate					
	0%		5%			
	Mean	Standard Deviation	Mean	Standard Deviation	T-Statistic	P-Value
1	162	0	171	2.08	7.49	0.0017
2	160	0	167	2.65	4.58	0.01
3	163	0	170	2.52	4.81	0.0086
4	163	0	170	2.52	4.81	0.0086

Treatment	5%		10%			
	Mean	Standard Deviation	Mean	Standard Deviation	T-Statistic	P-Value
1	171	2.08	177	3	2.85	0.047
2	167	2.65	175	2.52	3.79	0.019
3	170	2.52	177	5.13	2.12	0.101
4	170	2.52	177	5.13	2.12	0.101

Treatment	10%		15%			
	Mean	Standard Deviation	Mean	Standard Deviation	T-Statistic	P-Value
1	177	3	184	3.21	2.76	0.051
2	175	2.52	184	0.58	6.03	0.0004
3	177	5.13	186	6.24	1.93	0.129
4	177	5.13	186	6.24	1.93	0.129

T-Statistic: 4 Degrees of Freedom, 95% Confidence Level

Main Arena Model

Receiver Process
Rendezvous Process
Refueling Process
Future Need Process
Consolidation Process
Tanker Process
RTB Process

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15% Abort Rate

Comparison of Treatments	Mean	Standard Deviation	T-Statistic	P-Value
Treatment 1	184	3.21		
Treatment 2	183	0.58	0.53	0.624
Treatment 2	183	0.58		
Treatment 3	186	6.24	0.83	0.454
Treatment 3	186	6.24		
Treatment 4	186	6.24	0.00	1

T-Statistic: 4 Degrees of Freedom, 95% Confidence Level

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Results

- **Hypothesis 1 minimally supported.**
- **Hypothesis 2 partially supported.**
- **Hypothesis 3 supported with only 1 exception.**

Conclusions

- While tanker fuel consolidation has been shown to increase efficiency during mission execution, it has very little impact on the efficiency of operational planning.
- If the execution results are used rather than the planning results to determine the substitution ratio of KC-135s and KC-46s, the Air Force may find itself unable to meet strategic planning requirements.

Opportunities for Future Study

- Conduct study with KC-46 data. Mix of additional increased capabilities could effect results.
- Increasing fidelity of other factors will further increase validity.
  - Factors include: Aircraft turn times, aircraft abort rates, and multi-day operations.

Sponsor

United States Transportation Command - JDPAC
Air Mobility Command – A9

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Vita

Master Sergeant Jason Larimore graduated from Springfield High School in Springfield, Tennessee. He enlisted in the United States Air Force in November 1995 and earned qualification as a KC-135 boom operator in June 1996. He entered undergraduate studies through Embry-Riddle Aeronautical University's Distance Learning Program where he graduated Cum Laude with a Bachelor of Science degree in Professional Aeronautics with an Aviation Safety minor.

His first assignment was to the 912th Air Refueling Squadron at Grand Forks Air Force Base in June 1996. While there, he was upgraded to instructor and evaluator boom operator positions and flew combat missions in support of Operations Southern Watch, Northern Watch, Allied Force, and Nobel Eagle. In March 2002, he was selected to join the instructor cadre at the 509th Weapons Squadron located at Fairchild Air Force Base, Washington. His next Permanent Change of Station was to the 54th Air Refueling Squadron at Altus Air Force Base, Oklahoma. While there, he instructed and evaluated Formal Training Unit and Central Flight Instructor Course students in KC-135 operations. In August 2010, he entered the Graduate School of Logistics and Supply Chain Management, Air Force Institute of Technology. Upon graduation, he will be assigned to Wright-Patterson Air Force Base, Ohio.

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14. ABSTRACT

The United States Air Force (USAF) has selected the KC-46 to begin replacing the aged KC-135 fleet. One of the major differences between the KC-46 and the KC-135 is the KC-46's ability to be refueled. This allows for tanker fuel consolidation, or the refueling of one tanker by another. The effects of this capability on the efficiency of tanker operations must be quantified and included in determining an appropriate substitution ratio between the two aircraft. This ratio will be used to plan the retirement of KC-135s as the KC-46 enters operational fielding. This study utilizes simulation to determine the efficiencies gained by consolidation while maintaining a desired operational resiliency. The time fidelity of the model was also increased to determine the effects on the results. Air Mobility Command's (AMC) Analysis and Assessments Division (AMC/A9) provided a problem set for the simulation. The results of this study show that the largest benefit is realized by the ability of the tankers to transition between altitudes within a refueling track, rather than being restricted to the same altitude as is done in current models. Tanker consolidation and the increased time fidelity did not provide statistically different results. The effects stated in previous studies focused on post-mission data, not planning data. The lack of a significant decrease in the number of aircraft required shows that the benefits of tanker consolidation are much greater when it is used as an execution tool, rather than a planning tool. While the number of aircraft required in execution may be significantly decreased, the number required to meet the planning requirements is not.

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