



**ANALYSIS OF THE IMPACT OF DISTRIBUTED LOGISTICS OPERATIONS
ON MOBILITY AIRLIFT**

GRADUATE RESEARCH PAPER

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**DEPARTMENT OF THE AIR FORCE
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MOBILITY AIRLIFT

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Abstract

The increased likelihood of conflict with a near-peer adversary has increased the likelihood of historically safe airbases coming under attack. One concept proposed to minimize the effects of this challenge is a distributed basing network. However, the impacts of this paradigm shift on the air logistics fleet have not been analyzed. This study developed an agent-based simulation to replicate permutations of a distributed airbase network. The requirements of the bases dictated the behavior of the aircraft agents in the simulation and allowed for the analysis of simulation outcomes. It also allowed for the replication of differently sized basing networks to assess the relationship between the size and needs of the basing network and the resupply requirements.

The simulation was used to conduct numerous iterations of different distributed basing networks to assess the number of aircraft required to supply the bases. Trends in the data indicate relationships between distance, demand, and throughput capacity on the aircraft requirements. The simulation was also used to assess the effects of attacks on the transshipment nodes. These effects were studied and trends were identified to improve the understanding of how to build a more resilient logistics network.

The data from the simulation indicated significant relationships and trends that can inform strategic planners of optimal ways to implement a base supply network. This analysis led to multiple recommended courses of action. Finally, limitations of the simulation were noted and areas of future research were identified that were deemed critical to furthering the understanding of developing a more resilient basing paradigm.

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Collin A. Lohr

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I. Introduction

Background

The 2018 National Defense Strategy (NDS) identifies the re-emergence of “great power” states such as Russia and China and prioritizes the need for a resilient military force capable of surviving a potential conflict with these nations. Additionally, the 2018 NDS focuses on agile logistics that must be able to survive persistent multi-domain attack (Mattis, 2018). This is especially challenging in the Pacific theater due to large distances between ports and the threat from China’s ability to strike US staging locations with long-range ballistic missile attacks (Lazidis, 2016). One solution that has been suggested to solve this challenging problem is to develop a distributed basing network in the Pacific and increase the number of bases available for use (Priebe, Vick, Heim, & Smith, 2019). This would reduce the impact of potential disruptions or losses at one base, but the impact of a distributed logistics network on the aircraft moving supplies between these bases as well as the increased supply requirements of these bases has not been studied. This is a glaring omission and identifying the feasibility of this option and ramifications on the airlift fleet and logistics network are critical pieces of data to aid decision makers.

The first step in analyzing this problem is developing an understanding of the problem space and the proposed solution. The issue facing the US military at large, and the US Air Force specifically, is that emerging threats from great-power nations can reach and attack airbases (Lazidis, 2016). Chinese strategists intend to attack air bases because they see it as a weak point in the ability to project airpower. Furthermore, the

Chinese have the capability of executing these strikes at a number of bases that already exist inside the Pacific theater of operations (Mastro & Easton, 2017). US airbases can no longer be viewed as sanctuaries for aircraft or personnel, and this is concerning due to the lack of available basing options in the Pacific region.

One of the leading issues facing military planners is how to best operate in this contested environment. A proposal has been made to increase the number of bases available for use, hereafter described as “distributed basing”. In theory, this would limit the disruption to the military because disrupting one or more bases would have less of an impact on the military force and operation as a whole. Additionally, this would create more targets for the enemy to successfully strike to halt air operations. However, increasing the number of bases would have an impact on the logistics support network. The increased number of aircraft, frequency of flights, and impact to the logistics network that would be required to resupply and support these locations has not been studied.

The increased requirements on the logistics network required to support an increasing number of bases will directly impact the ability of the US military to develop and support these locations. However, the relationship between the number of bases and the support required in terms of aircraft and flight frequency has not been studied. This research intends to study the impact on the aircraft required to support a number of distributed bases and describe the relationship between the number of bases and the amount of support required. Additionally, this research will assess the impact of disruptions to the basing network to the aircraft required to support the logistics system.

This research will be used to determine the implications on the air mobility aircraft fleet and how to best posture the aircraft fleet in the future. The relationship between the numbers of aircraft required to support this concept will inform decisions on aircraft procurement to support the proposed logistics network. Finally, the insight gained from understanding how these aircraft are utilized and the distances they are expected to fly will inform future funding and development of aircraft that will be needed to support this concept of operations (CONOP).

Problem Statement

Decision makers in the Air Force and TRANSCOM need to know the best methods to develop a more resilient air logistics network in the Pacific theater. Through analysis of the constraints to the aerial delivery network and modeling of a variety of methods to increase the resiliency of the network, this research seeks to assist decision makers in improving the ability of the Air Force to project power in the Pacific theater. The purpose of this research is to determine if the current basing model in the Pacific theater is sustainable during conflict and to determine the key variables that change the workload of airlift forces. This will be determined based on the impact of disruption to the supply network, analysis of the effect of those disruptions, and the ability of the supply network to adapt and recover from disruption.

Additionally, there is a research gap in evaluating the feasibility of the proposed concept. Research has been done on different types of transportation networks and how to best optimize the use of the networks. However, there has not been an in-depth study on the relationship between the number of military aircraft required to support a network

of bases and the number, size, and distances of these bases. It is essential to determine this relationship because it will directly impact the feasibility of the concept.

Purpose Statement

The purpose of this research is to determine if the current basing model in the Pacific theater is sustainable during conflict and to determine the key variables that change the workload of airlift forces. This will be determined based on the impact of disruption to the supply network, analysis of the effect of those disruptions, and the ability of the supply network to adapt and recover from disruption.

Research Question

What are the impacts to the Mobility Air Forces in the implementation of a distributed basing and logistics network in the Pacific theater?

Investigative Questions

1. What is the relationship between the number and type of bases in theater and the aircraft required to supply these bases?
2. What impact, if any, does a disruption to a node have on the number of aircraft required to support the distributed network?
3. What are the critical variables in a distributed logistics model that effect sustainment and increase or decrease the crew force workload, for example: aircraft cargo capability, distance between distributed bases, support personnel required?
4. How sensitive is the model to changes in assets available, demand, and number of aircraft available?

Research Implications

This research could highlight deficiencies or strengths in the concept of distributed basing as a method for engaging against a “near-peer” adversary. It will inform the evaluations of the need to acquire more aircraft, a different type of aircraft, or shift resources to develop different basing models. Moreover, findings could provide recommendations to enhance the types of bases that exist within the distributed basing model.

Research Overview

This research paper will first provide an overview of the scientific literature that is most applicable to the concepts of adaptive basing and distributed basing. The literature review will cover both the military concepts and the scientific literature that describes logistics networks and simulation. Next, the paper will describe the simulation that was developed to represent the possible permutations of a distributed basing model in the Pacific theater. After describing the simulation, the experiments conducted using the simulation software will be discussed and the results of these experiments will be analyzed to determine the relationships between the various inputs to the simulation. Finally, the paper will draw conclusions based on these results and highlight potential real-world limitations, research impacts, and avenues for further research.

II. Literature Review

Chapter Overview

The purpose of this chapter is to develop an understanding of how a transportation network can be modeled, simulated, and analyzed. To build towards this understanding this chapter will first describe the fundamental concepts behind the Adaptive Basing concept of operations and how these concepts apply to the distributed logistics network. Additionally, the chapter will detail various methods of modeling and analyzing dynamic demand systems. The chapter will close by developing an understanding of how modeling and simulation can be used to solve the issue of analyzing the impact of variables on a dynamic transportation network.

Adaptive Basing and the Distributed Basing Concept

In early 2012, the United States enacted a shift in strategic policy that recognized a shift to the Asia-Pacific region. This shift also recognized the challenges the US military would face, namely that the main adversary in the region would pursue a strategy of Anti-Access/Area Denial (Defense, 2012). This guidance was further refined in the 2018 National Defense Strategy, instructing services to prepare for conflict with a great power in a contested environment (Mattis, 2018). This shift led to the rise in several concepts that aimed to change how military bases operate. These concepts all fall under the broad umbrella of “Adaptive Basing” strategies. To understand the focus of this research, it is useful to have an understanding of the applicable strategies.

The first concept of Adaptive Basing that this research will focus on is the concept of airbase protection and resilience. The idea behind this concept is that as bases

are more likely to come under attack in a contested environment, they must also be more resilient. Many options exist and have been studied to increase the resilience of an airbase, from hardened airbase facilities and aircraft shelters (Thomas, et al., 2015) to improved airfield defenses (Priebe, Vick, Heim, & Smith, 2019). The intent of this concept is to improve the airbase's ability to recover after an attack occurs and continue operations. However, these research concepts are still in the early stages and the theories presented in the research have not been tested in the real world, so the actual results and implications of the research are unavailable.

Another key concept of adaptive basing is the implementation of different types or sizes of bases. The current Air Force model is akin to a “hub and spoke” model of basing, with large consolidated hubs that are used as distribution points to reach the spokes. The adaptive basing concept of different types of bases focuses on how these “spoke” bases should operate. An early example of the most austere base is referenced by LtCol Davis's paper “Forward Arming and Refueling Points for Fighter Aircraft”. In this paper he discusses the concept of a bare bones airstrip that could be used as a Forward Arming and Refuel Point (FARP) for fighter aircraft in an anti-access environment (Davis, 2014). The concept of how to categorize bases is also discussed by Owen, who uses a tiered system and focuses on the airfield's length and weight bearing capacity to rank them between Tier 1 (large international airport) and Tier 4 (suitable only for vertical takeoff and landing) (Owen, 2017). A method of categorizing basing types by the amount of support and whether aircraft were assigned to the base was utilized in a RAND study, the type model they used is illustrated in Figure 1 below (Priebe, Vick, Heim, & Smith, 2019).

		Support Personnel Assigned to Operating Location	
		Yes	No
Fighters Assigned to Operating Location	Yes	Stay and Fight Base	
	No	Drop-in Base	Fighter FARP

Figure 1. RAND Methodology for Describing Types of Bases

The third concept that has gained prominence in adaptive basing is the concept of distributed basing. In an in-depth analysis of China's military capabilities and likely scenarios, one paper describes utilizing multiple airfields as a method of defense, forcing the enemy to spread out their ballistic missiles to more targets and hopefully increasing the survivability of each base (Cliff, Burles, Chase, Eaton, & Pollpeter, 2007). Davis expands on this concept in his discussion of fighter FARPs, specifically the analysis of how to pare down these bases in order to reduce the support footprint required (2014). Hatch builds on these papers and includes the possibility of utilizing acceptable highways and other paved surfaces as potential FARP locations (2015). Preibe, Vick, Heim, and Smith take the concept further, illustrating the positively correlated relationship between the number of bases that the US military could operate out of and the increased number of ballistic missiles required to incapacitate every base (2019).

These ideas form the basis of the adaptive basing concept. The Air Force is pursuing options to increase resilience of the bases, tailor the adaptive base to the correct requirements, and distribute bases to a wider variety of locations to best mitigate the threat of a contested environment in the Pacific theater.

The Use of Modeling and Simulation in Air Transport Networks

A model is designed to represent a system and capture the relationships involved in a real-world decision problem or phenomena (Ragsdale, 2004). Simulation is a technique that allows the model to be represented on a computer to analyze the system (Banks, Carson, Nelson, & Nicol, 2001). It has proven effective across a variety of disciplines due to the cheaper costs, ability to conduct experiments quickly, and ease of analysis (Panel, 2006). Simulations are also effective because they can reveal interactions that otherwise may not be apparent (Ören & Yilmaz, 2009). These advantages have led to a wide range of models and simulations being used from the micro-level to the macro-level that can analyze traffic flows and vehicle behavioral rules (Gabka, Susz, & Rosienkiewicz, 2016). Modeling has become so prevalent in the arena of logistics that Crainic, Perboli, and Rosano have proposed a taxonomy of modeling and simulation based on how the network to be analyzed can be described (2017). Additionally, simulation is effective because it can represent the changes in behavior and outcomes based on changes in the system, for example availability of infrastructure or vehicles (Crainic, Perboli, & Rosano, 2017). Clearly, modeling and simulation are effective tools to be used when trying to determine the feasibility of a new concept or approach.

Although many models have been used to study road traffic flows, the use of modeling is not limited to surface vehicles. Air travel demand has been modeled using discrete choice modeling to attempt to understand air travel consumer preferences (Garrow, 2009) as well as to understand the likely flow of pandemic diseases throughout the world. In these models, airports or bases serve as nodes, representing a location that an aircraft can move to and from during a time interval. Viewing the air transportation system as a logistics network decreases the complexity of the totality of air transport while still studying the interconnectedness and dependencies of the air transportation system (Rocha, 2016).

There are some commonly used terms that describe a logistics network in the scientific literature. The transportation network is a series of nodes that are connected by arcs. These nodes can be supply nodes, transshipment nodes, or demand nodes. Supply nodes provide the supply input, transshipment nodes can send and receive supplies, and demand nodes are the destination for the supplies (Ragsdale, 2004). The arcs represent the connections between these nodes. These terms are commonly used in the scientific literature and are also used when describing the study of military air logistics networks (Goldsman, Pernet, & Kang, 2002). The simulation designed to study the distributed basing concepts will reflect these node types and study the effects of the interconnected nodes.

Dynamic Inputs and Variation in Simulations

A key component of air transportation is flexible capacity. This creates unique challenges for modeling and simulation due to the dynamic nature of the network. Early

models of dynamic networks focused on stochastic network models, allowing for random variation to occur and analyzing the impact on the transportation network (Ran & Boyce, 1996). This is effective to better represent real-world conditions in which natural variations occur. Vehicle-based models were used to simulate the effects of traffic on networks as early as 1992 and is still widely used today (Ran & Boyce, 1996). This falls under the wider umbrella of “agent-based” modeling wherein the agent in the simulation behaves according to a set of rules, allowing the changes in outcomes to be studied based on the behaviors exhibited by the agents (Ören & Yilmaz, 2009). This is especially useful in transportation simulations where the system may change quickly or is ill-defined because it allows for analysis of dynamic systems (Chen, Cheng, & Palen, 2012) (Zheng, et al., 2013). Discrete event simulation is the most widely used type of simulation and is commonly used in Supply Chain Management and logistics decision-making (Jahangirian, Eldabi, Naseer, Stergioulas, & Young, 2010). The simulation designed to study the distributed basing concept will be a hybrid simulation, incorporating both of these concepts.

A major challenge in understanding the effectiveness of a logistics network is understanding how well it can operate in dynamic situations. Simulating a dynamic network is challenging because there are a variety of inputs that can change from day to day. When inputs are uncertain, they can be modeled using stochastic programming, describing the uncertainty through a probability distribution (Choi, Lee, & Park, 2018). Incorporation of these stochastic elements to the model has proven to be critical as solutions that rely on uncertain demand have been shown to be different than solutions that are based on a static average demand (Santoso, Ahmed, Goetschalckx, & Shapiro,

2005). Accurate assumptions and data are critical inputs to ensure optimization models are accurate and useful. However, if utilizing a procedure model or conducting early comparisons of options through simulations, more generalized data can still be effective and the requirement for accurate data is lessened (Kuhnt & Wenzel, 2010). This is critical because in many concept models, the concepts have not yet been developed or tested and therefore the only data available may be generalized data or assumptions.

Another source of variation in modeling the distributed basing concept is the physical locations of the nodes in the network. Mathematical programming has proven effective in optimizing the throughput and locations of nodes and hubs of large networks of up to 400 nodes (Campbell & O'Kelly, 2012). However, these mathematical models are concerned with large static networks in which the locations and demand signals do not change. More recent hub location research has focused on reliability metrics such as the resilience of the network to disruption. This may include probability of node failure (for instance, in the event of an attack) and illustrate the effectiveness of the network to adapt and respond to that failure (Kim & O'Kelly, 2009). Effective study of the distributed basing concepts will require these sources of uncertainty be included.

Analyzing Air Transportation Networks

Transportation network decisions can be categorized into three types: strategic, tactical, and operational (Wieberneit, 2008). Using this categorization, strategic decisions consider the location and structures involved in the network and tactical decisions concern the size and type of vehicles used. The primary purpose of this study is to determine the relationship between the strategic decisions of how the network is

formed (number of bases, location of bases, types of bases) and the impact on the tactical decisions that will be made to support that network (number of aircraft or other support required). Simulations have proven effective as a tool for making tactical and strategic planning decisions (Cartenti & Luca, 2012). Studies of air transportation networks also attempt to determine the importance of airports on a variety of metrics. This can be judged on the number of connecting airports, spatial coverage, or topological location in the network (Rocha, 2016). Criticality of an airport can also be analyzed based on the traffic rates through an airport (Sun, Wandelt, & Cao, 2017).

Computational experiments are commonly used to illustrate the results of a transportation system optimization study. If a known number of possible scenarios exist for a problem, scenario-based optimization can be conducted (Yin, Madanat, & Lu, 2009). However, it is more likely that the demand will be a continuous variable within a range. In this case, uncertainty can be modeled to increase or decrease variation to determine the resilience of the system and a series of experiments can be used to test the effectiveness of the system (Du, Jiang, Cheng, & Zheng, 2017). Within the bounds of this uncertainty, effective modeling and simulation allows for the manipulation of inputs to forecast possible outcomes and visualize the results of those choices (Gabka, Susz, & Rosienkiewicz, 2016). For example, the model can be used to create a low, medium, or high demand scenario that would illustrate the effects on the network for a variety of situations. This would then need to be subjected to sensitivity analysis to ensure that the result is both robust and repeatable under enough simulations to be considered accurate (Mahmoudabadi, 2014). When the model is run under numerous scenarios, the results can be analyzed to determine the relationships between the inputs and the variables.

Literature Gap & Summary

The adaptive basing concept proposed by the Air Force is a significant shift from how bases are traditionally viewed. The implementation of this concept would require additional infrastructure, training, research, and concept development, each of which comes at a financial and man-hours cost. It is critical that this shift is analyzed with a critical eye to ensure that the concepts are viable and that the Air Force understands the challenges of this model to avoid cost or time overruns.

Analyzing a new concept or model is inherently difficult due to the assumptions required, ambiguities in definitions, and variations between different ways the model can be implemented. Simulation and modeling provide an avenue to work through some of these ambiguities and analyze potential implementations to determine which, if any, method of utilizing this concept is the most effective. This has been used to analyze transportation networks, road networks, and basing hubs for airlines. However, simulation and modeling have not been applied to a concept similar to the adaptive basing concept or the distributed basing concept.

This study will apply the transportation network analysis techniques commonly used in other transportation and network industries to the Air Force's distributed basing concept. It will also show the pros and cons of the different permutations that the adaptive basing/distributed basing concept could take. Furthermore, it will show the value of simulation and modeling to the analysis of emerging concepts to better understand avenues for further research, training, and development.

III. Methodology

Chapter Overview

This chapter will describe the research design and methodology that was used to develop the experiments and research findings. The chapter will also cover the simulation development, methods, as well as data collection and processing. The chapter will conclude by detailing how the validity and reliability of the data were evaluated.

Research Design and Overview

This study utilizes the AnyLogic simulation software to develop a representative model of proposed ways the adaptive basing concept could become a reality. The model is designed to reflect three different types of bases representative of the concepts described in the adaptive basing concept. These bases are linked through the use of air transportation, representative of C-17 capabilities as indicated in AFPAM 10-1403, Air Mobility Planning Factors. The simulation was used to test a variety of permutations of number of aircraft available, number of bases utilized, resupply requirements of the demand nodes, and disruptions to the transportation network. The results of the simulation were then used to answer the primary research and investigative questions.

Assumption/Limitations

To be able to conduct the research, a few assumptions had to be established. The first assumption is that the bases that are used in the simulation are already capable to the level described, meaning they do not need additional materiel to increase their size or facilities. The second assumption is that the simulation will utilize the three types of bases discussed in the CONOP and that the types of bases have the same limitations,

demands, and constraints. Additionally, the model assumes that the C-17 model aircraft with Extended Range fuel tanks will be used to execute the CONOP. Although other aircraft could be utilized, the C-17 is the optimal choice based on the model for the distances flown. Furthermore, the simulation flight paths and airfield availability assumes that the host country is allowing US military to utilize the airspace or ground. The final assumption for the simulation is that Materiel Handling Equipment (MHE) is available at each of the bases to upload and download the aircraft upon arrival or departure.

A significant limitation in the research is the lack of specificity within the CONOPs available. This applies to the number of aircraft that would be used for a plan, the number of bases that would be used for the CONOP, the location of the various types of bases, and the number of personnel required to support the various types of bases. Instead, the CONOPs are largely focused on the ideas behind the plan. Due to the ambiguous nature of these CONOPs, the simulation was developed to test the intent of these ideas rather than the specific locations and demands. To understand the results of the simulation, the model was run numerous times in multiple configurations to understand the effect of different variables of interest on the results.

Moreover, an additional limitation of the research model is that it is focused on the air transportation network. Although there are a variety of ways to transport supplies across waterways, this produces more variables than the modeling simulation would be able to handle and does not fall within the research question, which is focused on the air transportation network. To mitigate the long-term effects of this deficiency, the simulation is focused on the initial time frame of using such a network (first 15 days, 360

hours), with the understanding that air transportation is faster and maritime assets would be effective and utilized over a longer timeline.

Simulation Overview

The AnyLogic simulation software allows for the development of a transportation and logistics network that is representative of the adaptive basing/distributed basing concepts. AnyLogic allows for hybrid simulations to occur, utilizing a variety of simulation techniques to accurately reflect the processes in which aircraft move within the logistics network. The logistics network is comprised of three different types of airbases. It is also comprised of the aircraft that are used to transport supplies between these bases. Finally, the required actions that occur when the aircraft arrive and depart the airbases are a critical component for how the air transportation network operates. The decisions made to develop the model are described in this section and further information can be found in Appendix A.

Basing Concepts and Location Development

The Main Operating Bases (MOB) serve as the supply node and are considered to be outside the disruption range of the enemy. The supply nodes operate at full capacity and do not face issues with supply or Maximum on Ground (MOG) in terms of the aircraft it can support at a given time. It is assumed that aircraft not represented in this simulation are being used to move supplies to keep the supply node fully stocked and not disrupt the flow of aircraft within the simulation parameters. Due to the distance from the MOB to the FARP, it was not feasible to launch missions from the MOB directly to the FARP and a transshipment point was required. The Limited Operating Bases (LOB)

serve as transshipment nodes, but fall within weapons range of an enemy and are subject to disruption. The LOBs have supply requirements and require resupply from the MOB periodically. The LOBs serve as the staging point to complete missions to the FARP which further depletes resources available to the LOB. In the event that the LOB falls below a critical supply level and supply from the MOB is not arriving in time, it is possible for the LOB to be resupplied from another transshipment node. The FARPs are demand nodes that are used as required and do not maintain a full-time logistics presence. Supplies that are delivered to the FARP are considered used and are removed from the simulation.

The base locations used in the model reflect actual airstrips in use in the Pacific theater. The MOB most likely to be used is Hickam Airfield, Hawaii due to the central location in the theater and the existing capacity at the airfield. Although some basing locations currently exist in this theater that would be adequate for LOBs or FARPs, the distributed basing model suggests that new bases may need to be built and that paved runways that are not currently in use may be required to launch missions and continue operations. Therefore, the model requires a variety of possible base locations to adequately scale and reflect permutations that may arise in developing the adaptive basing network.

To develop the database of possible LOB and FARP locations, airstrip data was collected from the Central Intelligence Agency (CIA) World Factbook. Airstrips were selected that were located between the MOB in Hawaii and the potential mission area identified as China (near Taiwan). The airfields were required to meet the Tier 2 terminal criteria (paved and at least 5,000 feet long) and would allow for mobility transport use as

well as fighter aircraft use (Owen, 2017). Once these bases were identified, the full list was filtered to ensure that the possible basing locations were located within realistic ranges to be used in the distributed basing concept. FARP locations were selected that were as close to China as possible while remaining outside the South China Sea, which is expected to be a likely conflict area should this concept be utilized. The full list of FARP locations includes 23 airstrips. This total number was deemed adequate to meet all demand configurations and was dispersed over a large enough geographic area to serve as a representative sample of possible FARP locations. Once the FARP locations were identified, LOBs were selected due to their placement between the MOB and the potential FARP locations. LOB locations that fell outside of 2,500 Nautical Miles from the potential FARP locations were filtered out of the database due to the aircrew mission requirements that would make these bases ineffective for FARP missions. Additionally, LOBs were prioritized that utilized pre-existing infrastructure and which would cause less diplomatic issues if they were to be used. However, diplomatic clearance issues were not prioritized or represented in the model. The final LOB listing includes 11 airbases. This number was deemed appropriate to serve as a representative sample of all possible LOB locations. The list of airbase locations and types can be found in Appendix A.

Once the potential airbases were identified, the locations were selected for use in the model. As the distributed basing concept has not been finalized, the basing locations could not reflect the real-world situation. Instead, the basing locations were selected for each experiment based on the desired analysis parameters. For example, if the desired analysis parameter was to determine the effect of distance between the LOBs and the MOB on the output of the model, base configurations were selected based on their

proximity to the MOB or FARPs. If instead the goal was to analyze a different parameter, bases were chosen with the least variation in distance to minimize the impact of this variable on the results of the model. The number of LOB locations and FARPs to be used was determined prior to running the simulation and this number of bases was selected from the available database. The bases were then placed in the simulation at the designated locations. An example of the base locations during a model run is shown in Figure 2.

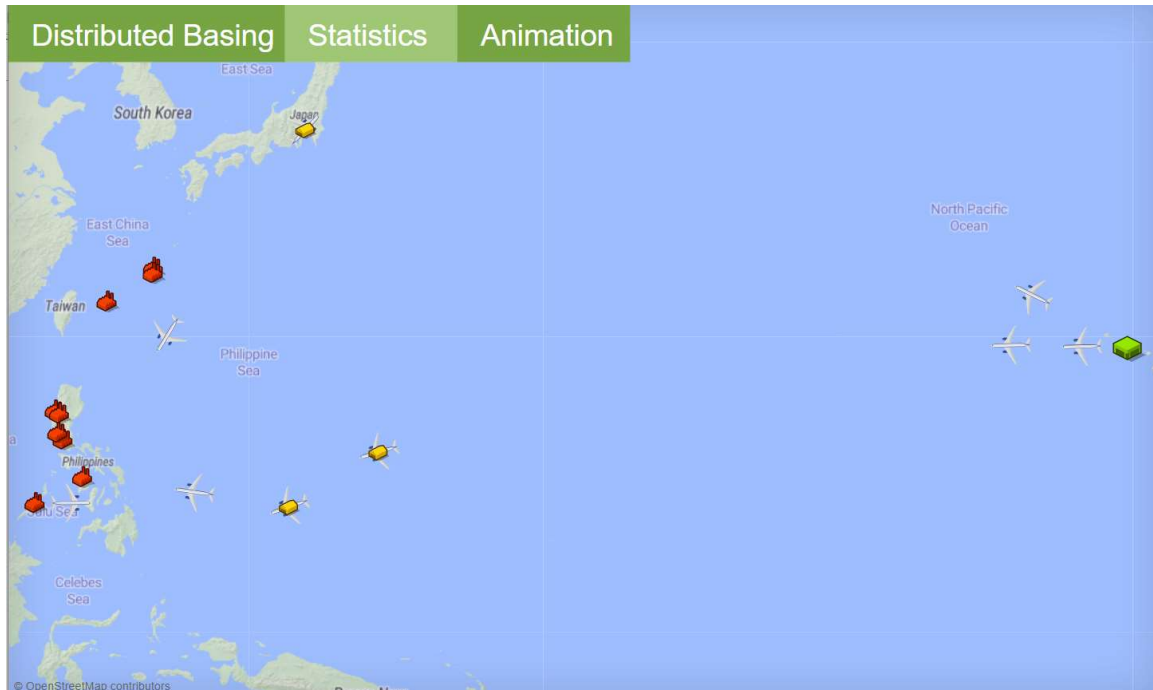


Figure 2. Example of Basing Locations During Simulation

Modeling Base Process Flows

The next step in modeling the airbases was to develop a process-based flow that would occur once the aircraft lands at a base. The simplest flow occurs at the FARP. In the FARP the aircraft lands, executes the FARP mission for a designated amount of time, and then departs the airstrip for a LOB. This is shown in Figure 3.

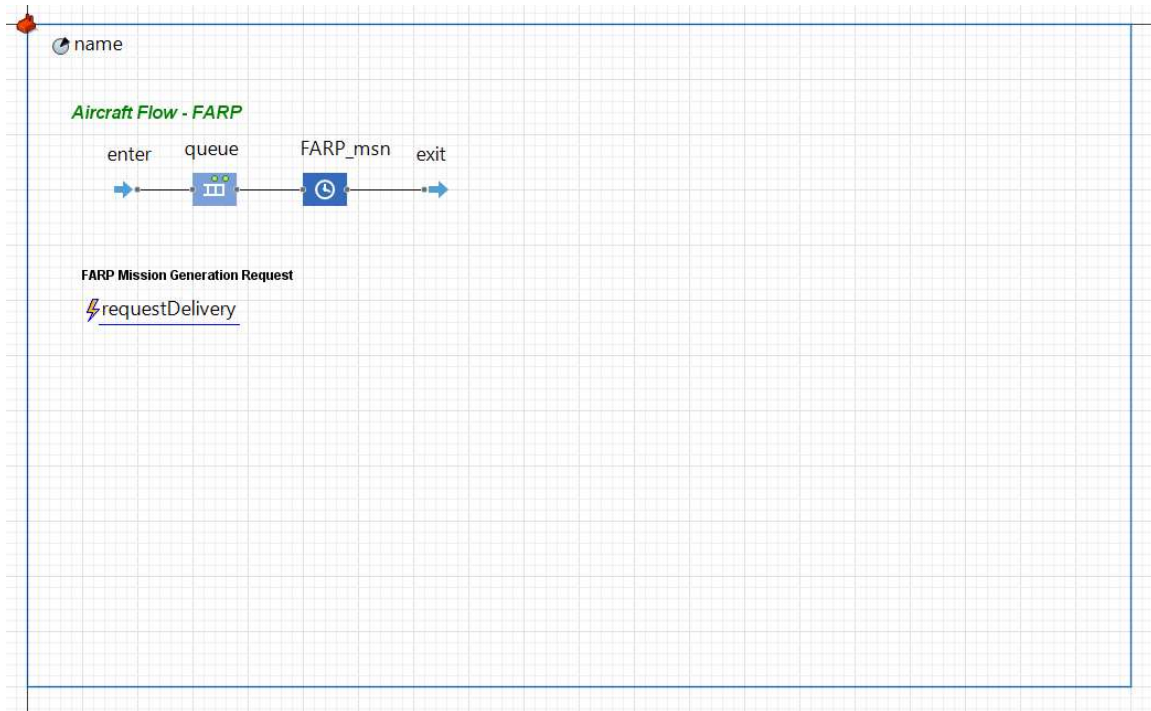


Figure 3. FARP Process Flow Diagram

A slightly more complicated flow occurs at the MOB. Here, the delay block functions as the upload and download time for the aircraft. When an aircraft arrives, it delays to represent a possible download/upload or the required maintenance inspections. Once those items are complete, the aircraft is ready for tasking and enters the queue for additional missions. When they are tasked with a resupply order, they exit the MOB. The MOB process is shown in Figure 4.

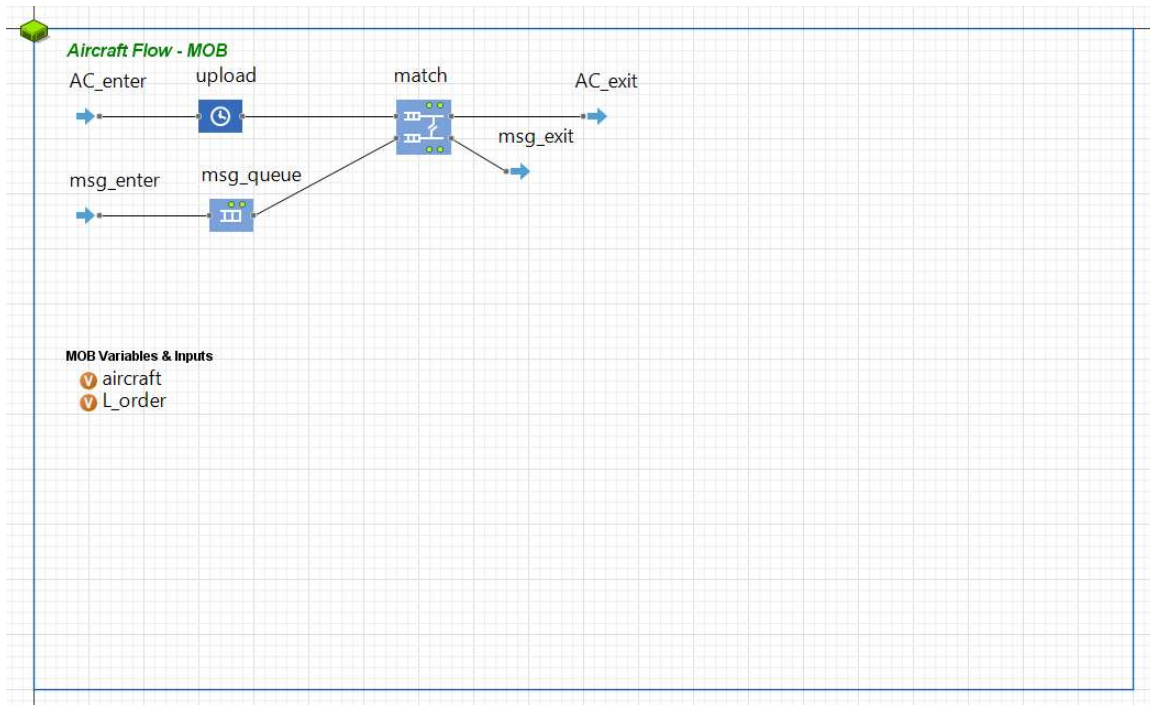


Figure 4. Main Operations Base Process Flow Diagram

The most complicated process occurs at the LOBs. The LOB process flow diagram is shown below in Figure 5. The aircraft arrive from another base and must be downloaded. This is depicted in the “Aircraft Flow” process portion of the diagram. After download, they can be tasked to resupply another LOB, complete a FARP mission, or return to the MOB to be ready to deliver more supplies. FARP missions and LOB missions are tasked and tracked through orders. When the LOB receives an order from a FARP or another LOB, the orders are process through the “Message Flow” portions of the Process Flow.

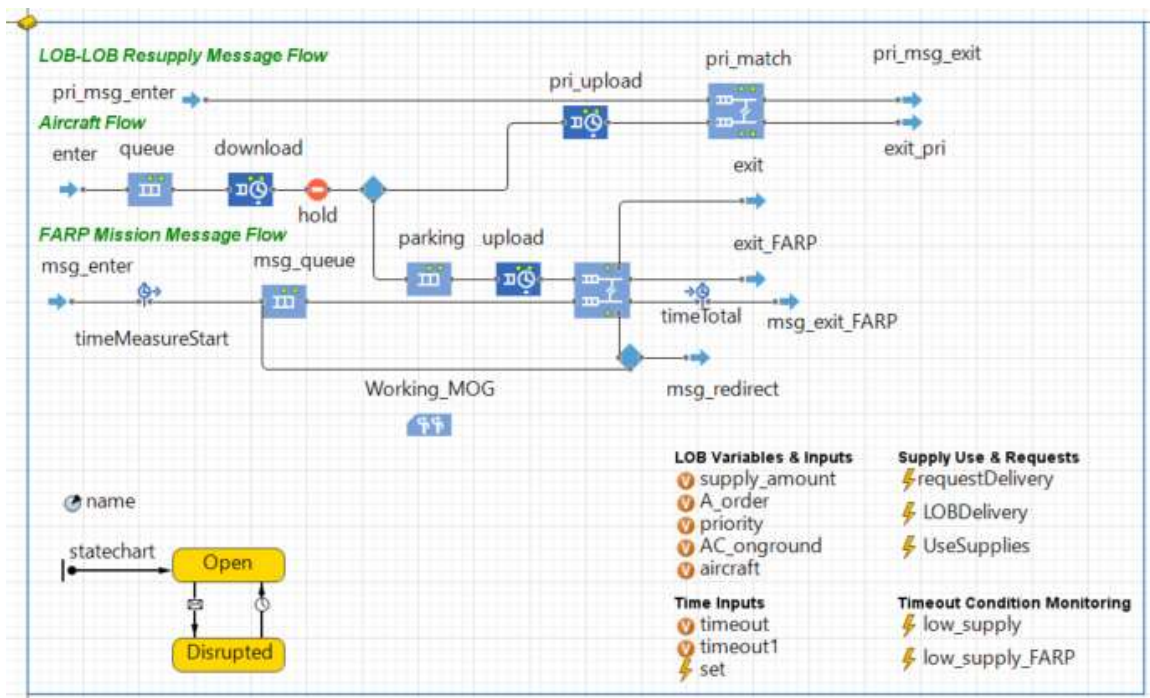


Figure 5. Limited Operations Base Process Flow Diagram

When an order arrives from a LOB in need of resupply or a FARP, the order enters the flow diagram through their respective “Message Flows”. When the message is matched to an available aircraft the C-17 aircraft agent is tasked. LOB resupply missions are considered the most critical, followed by FARP missions. A situation may develop where the LOB does not need supplies, but has FARP missions that need to be completed. In this situation, the FARP message would wait in the “match” queue. While the message is waiting, if an aircraft happens to arrive, the message will be matched to an aircraft. If instead, an aircraft does not arrive after a pre-determined amount of time (the “timeout1” variable) a mission request is generated at that LOB to summon an aircraft to the base. When this occurs, the prioritization level of the FARP mission message is increased (indicating that the message has been waiting in the queue longer than other messages) and the FARP mission message is returned to the queue. If an aircraft is

waiting in the match queue and no mission requirements arrive after a period of time dictated by the “timeout” variable, the aircraft returns to the MOB to be ready for further resupply missions.

The amount of space to conduct a download or upload, the MHE required to complete the download or upload, and the personnel required to operate the MHE impact the “working Maximum on Ground (MOG)” of the location. A pre-determined working MOG can be set for the LOBs and is represented by the “working_MOG” pool of resources that reflects the availability of space, personnel, or MHE. If an aircraft is in the upload or download queue and all available working_MOG assets are currently utilized, the pre-determined queue delay will not start until a working_MOG asset is released. This represents a situation where the required time to upload or download an aircraft cannot start because there are not enough assets available to complete the event.

The supply level at the LOB begins at a set value (4 days’ supply as calculated by the supply use rate) and then decreases through three different ways. Supplies can be used at the LOB over time at a user defined rate, supplies can be used to complete FARP missions, or supplies can be moved to another LOB that is in a critical supply state. Supplies are primarily requested from the MOB through a resupply order. In the event that an aircraft is not available at the MOB to resupply the LOB and supplies reach a critical level, an order is instead sent to a LOB to complete resupply at the critically low airbase.

The LOB diagram also has two of the “simulation failure” items included as events, shown under the title “Timeout Condition Monitoring”. In the event that a LOB runs out of supplies (the value “supply_amount” reaches zero) this is considered a failure

for that iteration of the simulation. This will stop the simulation and record the stop time and other parameters of note for further analysis. Similarly, if a FARP resupply message is not matched to an available aircraft within 72 hours (3 days) it is considered an iteration failure. These two events serve to provide a baseline requirement for the simulation. The available aircraft must be able to supply all bases that need supplied and continue FARP operations in a timely manner for the pairing of aircraft to parameters to be considered successful.

Modeling Aircraft Behavior

The aircraft used in the model reflect the capabilities of a C-17 as described in AFPAM 10-1403. A standard aircraft block speed of 400 knots is used to define movement parameters and the upload and download times are normalized around a standard planning factor of 1+30 with a deviation of ± 30 minutes. The FARP mission timeframe is 120 minutes with a standard deviation of 30 minutes to reflect the times provided by LtCol Davis in his concept paper (Davis, 2014). Although the aircrew aboard the aircraft would be duty-day limited, the simulation is unable to reflect this pairing and restriction and the aircraft is assumed to be able to operate and crew-swap without additional delays at any LOB or MOB. The locations of the LOBs are such that aircrew would be able to move to or from the LOB and return within duty day limitations.

The aircraft move between bases through a series of agent-based modeling rules. Agent-based modeling allows for the aircraft to react to the environment and priorities provided to achieve goals (Zheng, et al., 2013). This allows the aircraft to move

dynamically within the system based on pre-defined transitions between “states” such as flying, on the ground, or awaiting upload. These states are depicted by a flowchart, shown in Figure 6.

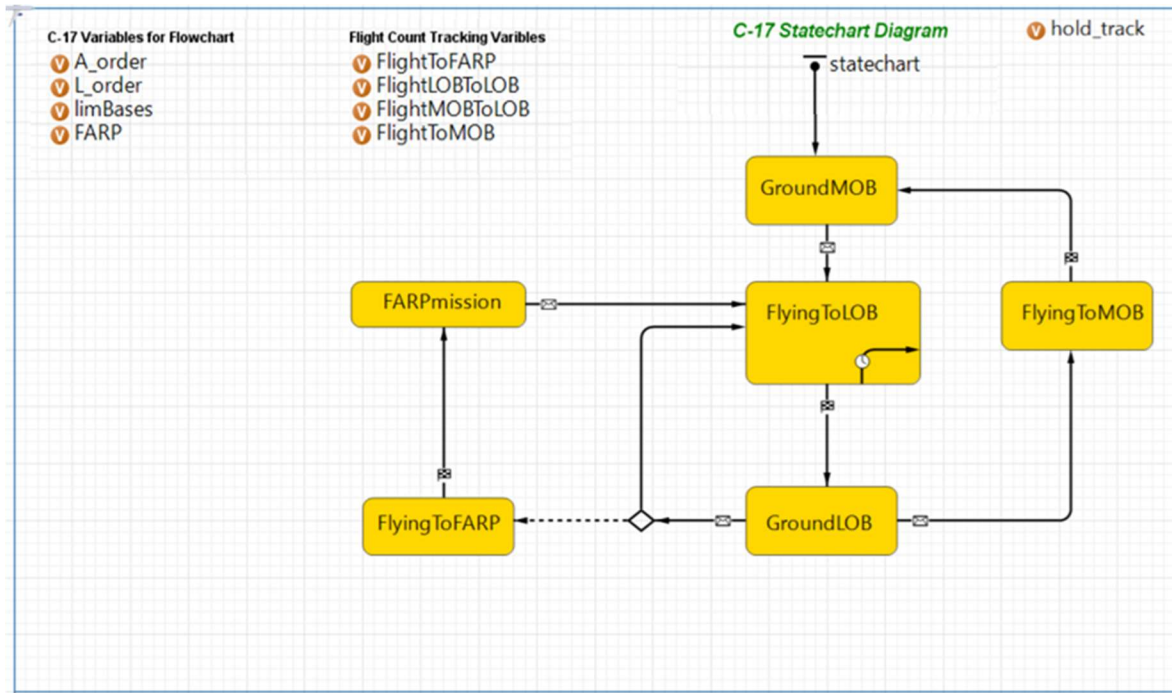


Figure 6. C-17 Statechart Diagram

The statechart defines the behavior of the aircraft within the simulation. At the beginning of the simulation a number of aircraft are created based on user defined inputs. Each C-17 begins on the ground at the MOB. When a mission tasking message arrives and is matched to a C-17, a state change is triggered. This is depicted by the line between the “GroundMOB” state and the “FlyingToLOB” state. The mission message contains the location where the resupply message will occur and during the “FlyingToLOB” state the C-17 is in transit. Upon arrival at the LOB, the C-17 transitions to the “GroundLOB” state where the C-17 agent enters the LOB Process flowchart at “AC_enter” shown in Figure 5. There are three possible outcomes from a C-17 agent in the LOB Process Flow

diagram. When the C-17 agent exits the LOB Process Flow diagram, the type of mission tasking determines which state the agent enters next. This process continues throughout the simulation, continually updating the behavior of the C-17 agent based on the current requirements of the various bases in the simulation.

The C-17 statechart also includes the variables to track how many missions each C-17 agent completes during a simulation run. These variables are listed under the “Flight Count Tracking Variables” portion of the statechart. This allows for the simulation to compile aggregate counts of each type of mission to determine the effects of the simulation parameters on the ratio of missions completed.

Disruption Events to the Logistics Network

A disruption event to the logistics network occurs at the LOB level. A disrupted LOB is designed to illustrate the effects of an enemy attack on the LOB. When a LOB is disrupted, it moves from the state “Open” to the state “Disrupted”. When this occurs, the base is essentially “closed” as an operating location, but will still consume or use the daily resource requirement. Mission orders are not sent to a disrupted LOB and instead are routed to the other open LOBs. Any aircraft that are on the ground at the LOB and are capable of leaving the airfield, will do so. This represents a situation where there is enough warning of an attack to have aircraft depart the base. However, an aircraft in the process of downloading would be unable to egress and instead will be stuck on the ground for the duration of the disruption.

A disruption event also impacts the aircraft that are currently inbound to the disrupted LOB. If an aircraft has a mission to the LOB, it will continue the mission to the

LOB until it is within range of the location, because the LOB may re-open while the aircraft is enroute. If instead the LOB is still closed when the aircraft nears the base, the aircraft will be re-routed to an open base, representing a situation where the aircraft is required to divert from the primary mission location.

Disruption events incorporate two variables that can impact the flow of the simulation. The first variable is the length of the disruption event. This represents how long it takes a LOB to become operational after an attack. For a given simulation run, the length of the disruption is a fixed time and is set as part of the initial simulation parameters. The second variable is the rate at which a random LOB in the simulation is disrupted. This rate is an average daily rate of disruption (i.e. 2 disruption events per day). However, because this is an average daily rate rather than a fixed rate, the frequency of disruption can vary and some days may have significantly more or significantly fewer disruption events than the average.

If a high enough daily disruption rate or length of disruption is selected, it is possible to disrupt all available LOBs. If this occurs, an aircraft enroute to a LOB may not have an available divert option. In this scenario, the aircraft will hold for up to 2 hours for a LOB to open. If no LOBs become available, the aircraft would be forced into a ditching or emergency landing situation. This would be a failure condition and the simulation would pause or terminate at this point.

Experiment Capabilities and Data Collection

This section will first describe the capability of the AnyLogic software to conduct various types of experiments. Next it will describe the variables of interest to this study

and how these were manipulated to gather data on the various iterations of the simulation. Lastly, it will describe how the data was gathered and prepared for further analysis.

The AnyLogic software allows for multiple ways to run the simulation and collect data on the iterations that occur. The simulation has been designed to allow the user to input a variety of parameters to analyze the effects on the situation as they change. The primary variables of interest during the simulation run were the number of aircraft, the mission requirement rates for FARPs and LOB resupply, the working MOG, disrupt rate, and disrupt frequency. In the basic simulation model, these variables can be input prior to beginning a simulation run. This input screen is depicted in Figure 7.

Pacific Air Fleet Model : Simulation - AnyLogic Personal Learning Edition

Pacific Air Fleet Model

The concept model of a distributed logistics network in the Pacific Theater. Please select initial inputs for the simulation below.

20	Aircraft Available (integer)
2.0	LOB Supply Use (supply amount used per hour)
1.0	FARP Demand (number of requests per day)
4	Working MOG per LOB (integer)
12.0	Length of LOB Disruption (hours)
1.0	Rate of LOB Disruptions (number of disrupt events per day)

- aircraft
- 20 FARPdemand
- 1 supplyUse
- 2 MHE
- 4 disruptTime
- 12 disruptRate
- 1

▶ ■ (x1) (P) x10 (b) (P) ■

Figure 7. Simulation Model Input Variable Screen

Using a single simulation run allows for the user to analyze how the simulation operates during one simulation with a given set of input variables. It also allows the user to navigate through the various stages of the model and determine how the agents interact. For example, this allows the user to observe the process flow at the LOB and determine where a bottleneck is occurring. It also allows the user to analyze data from the simulation run to determine the impact to variables that change over time during the simulation. For example, this is a useful method to determine the distribution of how long it takes a FARP order to be filled or the statistics of the supply level at each LOB. Although this is useful to determine that the model is working correctly and to visualize the Distributed Basing concept in action, it does not allow for easy comparisons across model runs for different variables.

The most effective way to determine the effect of a variable on the simulation is for the user to run a number of iterations of the model with a given set of variables. The Central Limit Theorem states that as the number of samples (iterations) increases, the mean values of the samples take on a normal distribution. Generally, this requires at least 30 samples (Aberson, Berger, Healy, Kyle, & Romero, 2000) (Norman, 2010). Once there are enough iterations of each set of simulation parameters it is possible to compare the mean values of the simulation iterations to determine the relationships between the variable of interest (the variable we are changing) and the control (unchanged) variables. Through the AnyLogic software, this capability is provided by creating a Parameters Variation experiment.

The Parameters Variation experiment function allows the user to complete a pre-determined number of iterations of the simulation in rapid succession. 50 iterations were

run for each set of variables in the experiments in order to exceed the minimum suggested by the Central Limit Theorem. The Parameters Variation experiment function also allows the user to choose whether a given variable is fixed or changed within a range. The range of variation and the step value of the variable can be defined as inputs to the experiment. This is useful if the user desired to know the effect on supply use rate and FARP demand on the number of aircraft needed to support each rate. The supply rate and FARP demand could be entered as fixed variables and the aircraft would be a range of variables with a defined integer step rate (as it is not possible to have half of an aircraft). Then the effect on number of missions flown, types of missions flown, or whether the simulation was terminated early for the given set of parameters could be analyzed. This type of analysis is effective in determining the answers to each one of the research questions proposed by this study.

The simulation was designed to collect data on the variables of interest at the end of the simulation. Upon the simulation ending multiple database files were updated simultaneously which tracked the inputs variables and the time that the simulation terminated. If the LOB supply level reached zero or the FARP mission message wait time exceeded 72 hours, the simulation was terminated and the time was recorded. Otherwise, the simulation was terminated at 360 hours (15 days). Within the Parameters Variation experiment framework, the input parameters and the time that the simulation ended was recorded. After the iterations are complete, the resulting data is a histogram that can be used to show the variable of interest plotted against the time of simulation completed. A successful simulation run would show the completion as a count at 360 hours whereas the unsuccessful run would result in a time less than 360 hours. The

resulting counts of the variable and the distribution of time form a histogram depicting the possible range of time outcomes for each variable manipulated. Once one set of this data is generated, the fixed value variable can be changed and the iterations repeated. The resulting histograms depicting the model success rates across the range of variables can then be compared to determine the relationship between the range of variables (which are then a “fixed” range) and the fixed variable (that is now being “varied”) that is being manipulated.

When a simulation or model is used in an experiment, there are always concerns about the efficacy of the model. Although it is impossible for a simulation to match reality perfectly, it is important that the simulation runs reliably and produces the expected results in known situations. For example, if there are no obvious constraints in the Distributed Basing simulation, the simulation should not terminate prior to hour 360. This was validated by increasing the throughput capacity at each operating location (no ground handling constraints) and then increasing the number of available aircraft above a value that would be a constraint on the system (notionally, 100 was chosen). In this situation, the model should not fail to meet the goal of 360 hours. These parameters were used to run the model through a wide variety of demand situations, LOB quantities, and FARP quantities to ensure the model did not fail prior to the successful timeframe.

Experiment Categories

Four inputs were determined to be critical to the simulation and of interest to the possible development of a distributed basing network. These inputs were distance, demand, working MOG, and the effect of disruptions. To isolate the impact of each of

these inputs, different experiment parameters were used. This section will briefly describe the initial assumptions of the experiment designs to better understand the implications of the final results. In all cases, the impacts of the variables were assessed by comparing the total number of aircraft required to support a given configuration.

The distance experiments were designed to isolate the effect of distance on the logistics network. The results of the distance calculations between the various basing options are displayed in Appendix B. Once the distances between the bases were known, two distance experiment profiles were developed. The first profile created two sets of notional bases located along a straight-line distance between the MOB and a cluster of FARPs. This reduces any error in total distance and solely uses the distance from the MOB to the LOB and the distance from the LOB to the FARP. The second profile was designed to isolate the effect of distance between the LOBs and the FARPs. LOBs were selected that were equal distances from the MOB location, but which were different distances to the FARPs in use. This reduces any effect of the LOB to MOB distance and isolates the effect of LOB to FARP distance. The third experiment is designed to synthesize the results of the first two experiments and determine which factor (if either) is more predictive on the overall aircraft requirement to support the logistics network. This will be accomplished by analyzing the results of three different LOB locations that vary in overall distance, LOB/MOB distance, and LOB/FARP distance.

The second class of experiments are the demand experiments. These will analyze the effects of different “demand” drivers to include the number of bases, frequency of FARP missions, and the impact of supply use at the LOBs. The first demand experiment was designed to compare configurations of different numbers of LOBs (2-5 bases) across

a variety of hourly supply use rates (2-10 units per hour). The second demand experiment analyzes a large number of LOB supply use requirements and FARP demand requirements across varying numbers of bases to detect any trends while controlling for the effects of distance. The third demand experiment compares 4 configurations of LOBs and FARPs across demand ranges to determine the effect of the number of bases on the number of aircraft required.

The working MOG experiment is designed to determine the impacts of a below-optimal working MOG. In all other experiments, the working MOG is high enough to have no impact on the results. In this experiment, the working MOG is reduced to determine the effect on a given LOB/FARP configuration. Three separate FARP demand/LOB supply use profiles were utilized to determine if the working MOG effect showed any trends based on increased or decreased demand.

The disrupt class experiments are designed to determine the effect of a LOB disruption on the distributed basing network. LOB configurations were developed to utilize between three and seven LOBs and assess the effects of the rate of disruption (0 to 4 events per day) and the length of disruption (0 to 48 hours disrupted). The same configurations of LOBs and FARPs were used in the rate and length experiments to allow for comparisons between experiments to determine which type of disruption (more frequent or longer lasting) had a larger impact on the network. A summary of these experiments is shown in Table 1.

Table 1. Planned Experiments

Experiment	Description
Distance Analysis 1	Isolate MOB to LOB & LOB to FARP distance, remove effect of overall distance
Distance Analysis 2	Isolate LOB to FARP distance, minimize effect of MOB to LOB distance
Distance Analysis 3	Determine which effect is greater between MOB/LOB distance or LOB/FARP distance
Demand Analysis 1	Compare number of LOBs to the supply use rate, minimize the effects of distance
Demand Analysis 2	Analyze the ratio of required aircraft compared to the “expected” number of aircraft that should be required in a large dataset
Demand Analysis 3	Compare 4 configurations of LOBs/FARPs with proportional demand variables
Working MOG Analysis	Analyze the effect (if any) of a variety of working MOGs at LOBs
Disruption Rate Analysis	Analyze the effect on a predetermined configuration of multiple disruption rates (LOB/FARP configuration matches Disruption Length Analysis)
Disruption Length Analysis	Analyze the effect on a predetermined configuration of multiple disruption lengths (LOB/FARP configuration matches Disruption Rate Analysis)

IV. Analysis and Results

Chapter Overview

This chapter will first build a foundation of understanding why the study is vital by analyzing the data obtained from the simulation. The results from the four categories of experiments will be presented and discussed. Discrepancies or known flaws in the simulation data will also be highlighted. Next, the overall results and implications of these experiments on the possible validity of the adaptive basing or distributed basing concept will be discussed. Finally, the investigative questions of the research study will be addressed.

Distance Experiment Data

The first distance experiment utilized two notional sets of 3 LOBs located along a straight line drawn between the MOB and the cluster of FARPs that would be used for the missions. By utilizing a straight line, the experiment maintained the same overall distance from the MOB to the FARP cluster and the only distance variable was the location along that line of the LOBs. In the first set of iterations, the 3 notional LOBs were placed at a distance 25% of the way between the MOB and the FARPs. This places the LOBs 2,129 km (1,150 NM) from the MOB and 6,388 km (3,449 NM) from the FARP cluster. In the second set of iterations, the LOBs were placed 75% of the way between the MOB and the FARPs. This places the LOBs 6,388 km (3,449 NM) from the MOB and 2,129 km (1,150 NM) from the FARP cluster. The simulation was then run with three different FARP demand levels for each configuration across 18 different

numbers of available aircraft. The results for how many aircraft of each configuration (150 maximum possible per iteration) are depicted in Figure 8.

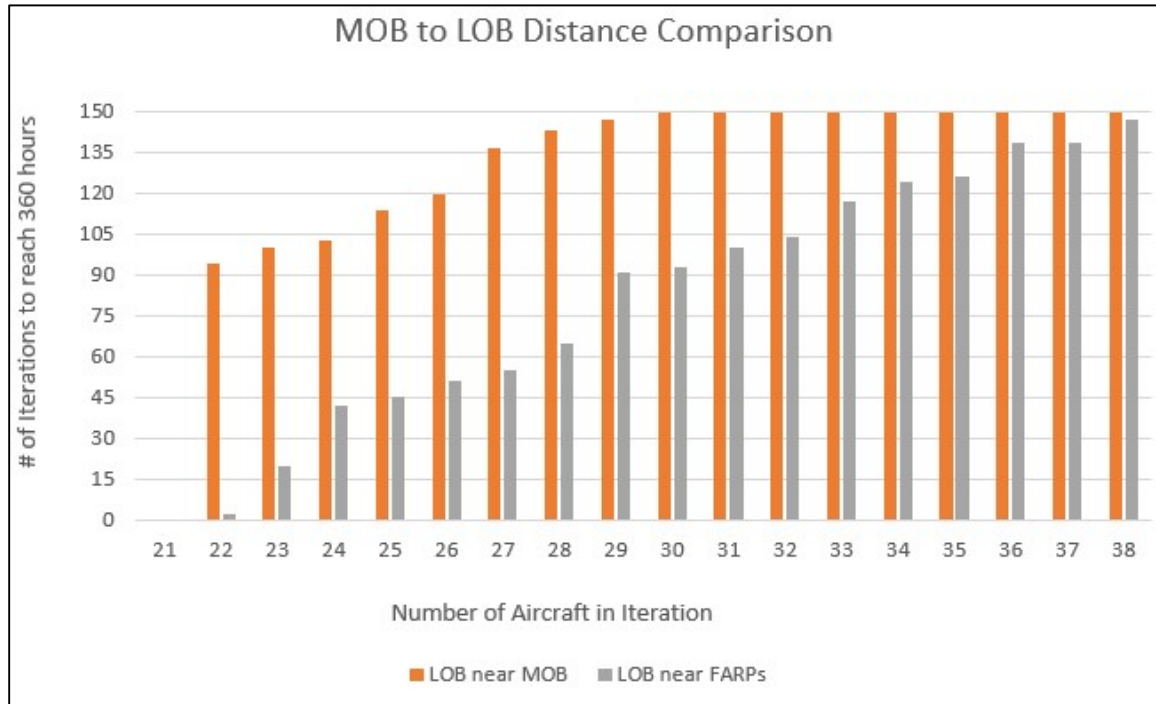


Figure 8. Distance Experiment 1 Results

The vertical orange and grey bars in Figure 8 depict the number of simulation iterations that reach the end of the simulation timing (360 hours). A simulation that fails to reach the 360-hour mark indicates that either a LOB supply level reached zero or a FARP mission was not met within 72 hours. Therefore, a higher number of iterations reaching the 360-hour mark indicates a more sustainable and successful result. When the values reach the 360-hour mark and do not dip below this amount, it indicates that adding more aircraft does not produce any gains. Figure 8 shows the effect that varying only the location of the LOB cluster with respect to the MOB has on the overall aircraft requirements.

The location nearer to the MOB reaches a 100% success rate (all 150 iterations reach 360-hours) with 30 aircraft. The location further from the MOB does not reach 100% success with the maximum number of aircraft analyzed (38 aircraft). The completion rate is significantly higher for the LOB location closest to the MOB than the LOB location near the FARPs. This holds true for each of the subcategories of the data as well (which analyzed 3 different values for the supplyUse variable) and indicates that the LOB distance from the MOB has a strong effect on the number of aircraft required to support the base network. The further a LOB is located from the MOB, the more aircraft that will be required to make the network viable.

The second distance experiment utilized two LOB locations (Marshall Island and Wake Island) that were located approximately the same distance from the MOB (3,665 km and 3,687 km respectively). However, there is a difference of approximately 1,000 km between these LOB locations and the selected FARP locations (average distance to FARPs 5,068 km and 4,020 km respectively). This minimizes the difference in the LOB locations with reference to the MOB, but allows the experimenter to determine any effect of the increased distance to the FARP. Similar parameter profiles were run as in experiment one and the results are depicted in Figure 9.

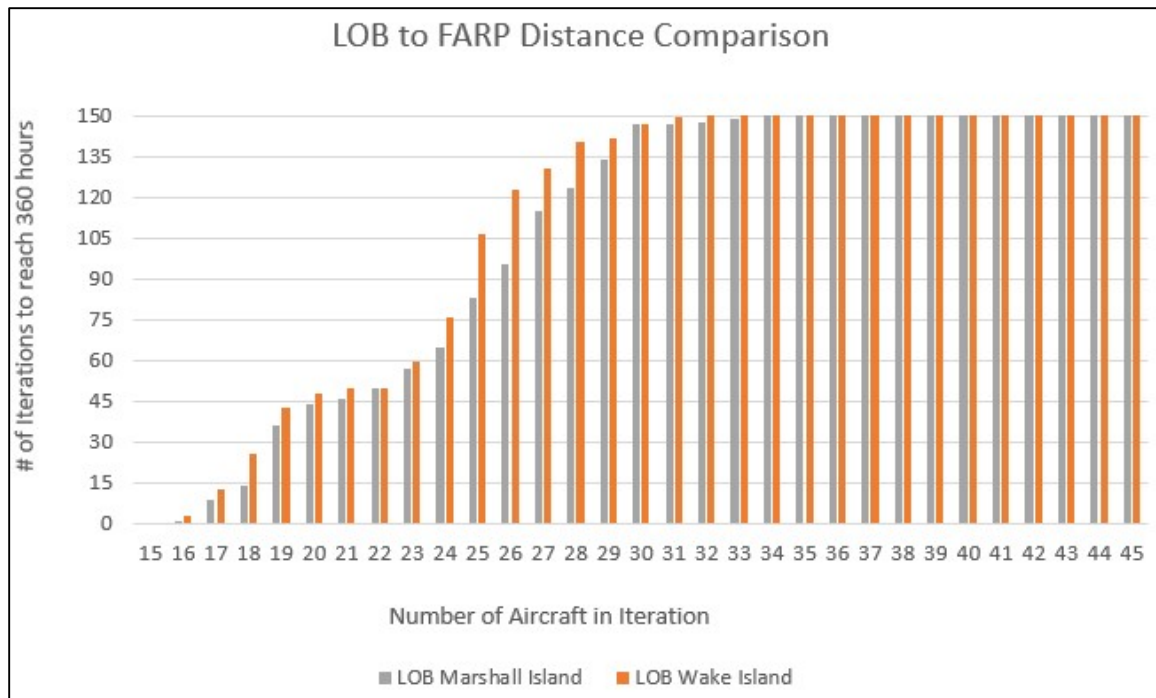


Figure 9. Distance Experiment 2 Results

Figure 9 should be interpreted in the same manner as Figure 8. Wake Island is approximately 1,000 km closer to the FARP cluster, indicating less overall distance. The data above shows that in some configurations (25-29 aircraft results specifically), this reduced overall distance proved to be an advantage. We can therefore conclude that overall distance will have an impact on the number of aircraft required. The longer the overall distance from the MOB to a FARP location, the more aircraft that will be required.

The third distance experiment was designed to determine which variable (overall distance, MOB/LOB distance, or LOB/FARP distance) has the greatest impact on the overall aircraft requirement. Three LOB locations were selected based on their distances from the MOB and FARPs. The locations and their respective distances are summarized in Figure 10. The other parameters (demand rates, aircraft available, etc) were

unchanged from the previous two distance experiments. The results of this experiment are shown in Figure 11.

(all dist. in km)	Dist to MOB	Dist to FARPs	Round Trip Dist
Anderson	6,097.1	2,646.0	8,743.1
Yokota	6,235.7	3,058.1	9,293.8
Honiara	5,714.1	5,076.6	10,790.7

Figure 10. LOB Distance Details – Distance Experiment 3

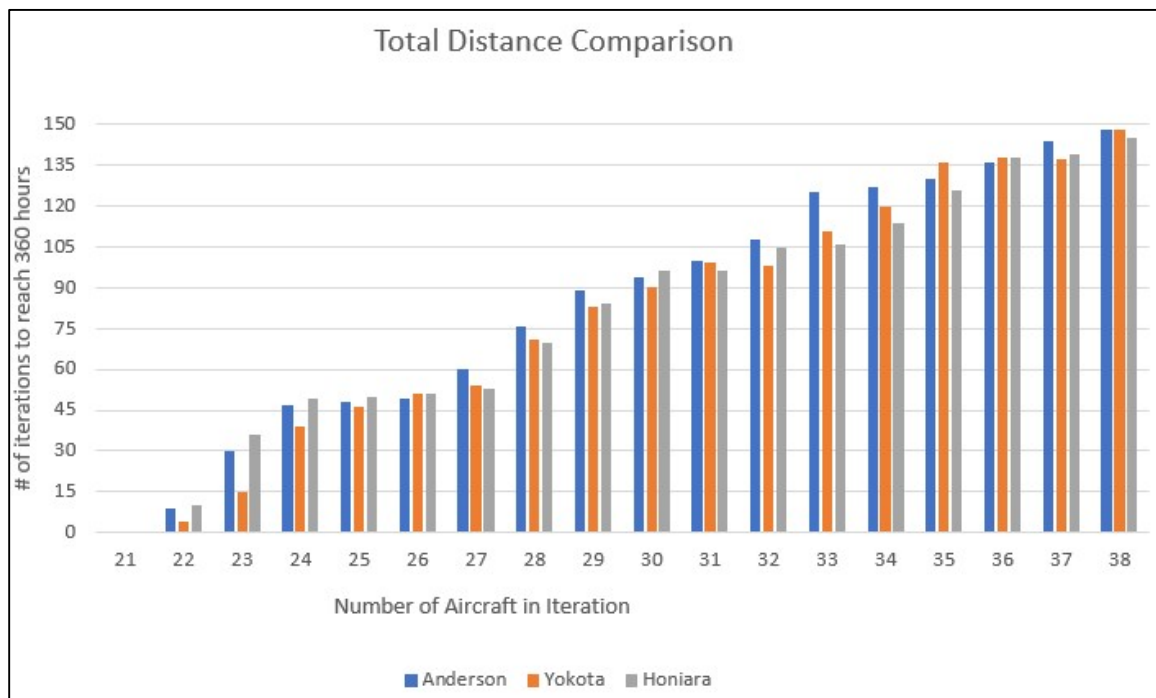


Figure 11. Distance Experiment 3 Results

As with Figure 8 and Figure 9, a higher number of iterations reaching 360-hours is desired. Anderson Air Force Base has the highest overall success rate across the spectrum, followed by Honiara, and then Yokota. When we compare Anderson and Yokota, this data matches what we have seen in the first two distance experiments. Yokota is further round trip and further from the MOB. It should have the lowest success rates. It becomes more interesting when we view these two bases in comparison to

Honiara Airport. Honiara Airport is approximately 1,500 km further in round trip distance than Yokota, but still outperformed the Yokota location. This suggests the proximity of Honiara Airport to the MOB outweighs the increase in overall distance. Although there were times that the Yokota location outperformed the other two, the data suggests that the most impactful distance metric is the distance from the MOB to the LOB. But it also suggests that if locating the LOB closer to the MOB significantly increases the overall distance, the gains from closeness to the MOB may be lost.

Demand Experiment Overview

The demand experiments discussed in this section were designed to build an understanding of the impacts of individual base demand on the distributed basing model. Many events in the simulation can dictate how an aircraft agent moves in the simulation. If we start with the understanding that all aircraft eventually return to the MOB barring any other demands, we can consider the MOB to be the furthest point “backward” in the simulation. If this is our reference point, the furthest point “forward” would be a FARP and the points in between these two extremes are the LOBs. The aircraft in the simulation are pulled from the MOB to the LOB based on two factors, the requirement to resupply a LOB and the requirement to complete a mission to a FARP. The event that drives an aircraft from the LOB to a FARP is a FARP mission.

The basic understanding of what drives aircraft movements in the simulation allows us to make some predictions on the how the aircraft should behave. At a minimum, we should expect one aircraft to move from a LOB to a FARP for each FARP at a rate of the daily FARP demand (defined in the simulation by the “FARPdemand”

variable, hereafter referred to as *FARPdemand*). Additionally, we expect the aircraft to move from the MOB to the LOB at a rate required to resupply the LOB supply use rate per hour (defined in the simulation by the “*supplyUse*” variable, hereafter referred to as *supplyUse*). A FARP mission requires one aircraft to complete. An aircraft can resupply on average 12 “units” of supply per mission flown from the MOB to the LOB.

Therefore, the hourly supply use rate at a LOB roughly approximates how many aircraft would be required to replenish the supplies approximate the following equation:

$$(Number\ of\ FARPs \times FARPdemand) + (Number\ of\ LOBs \times supplyUse)$$

However, this does not account for all of the aircraft in the system. Because each of these events moving “forward” requires the aircraft to move “backward” to receive another mission, we would expect this number of aircraft to be up to double this value.

The demand experiments were designed to test whether this assumption is correct and if the assumption is incorrect, the ways in which the aircraft requirements can be better understood.

Demand Experiment Data

The first demand experiment was designed to determine the relationship between the number of LOBs used in a configuration and the effect of increasing the supply use at each LOB. Five LOBs were selected for use in this experiment based on their similarities in proximity to the MOB and the FARPs. The LOBs utilized in the 2 LOB configuration were the furthest away from the FARPs/MOB, and subsequent LOB additions added the next furthest LOB in order to minimize the effect of distance. Based on this, the data is expected to show a slight decrease in the aircraft required for each additional LOB,

relative to the demand if the added LOB were instead further away. The LOBs utilized in distance order (furthest listed first) are shown in Figure 12.

Lat	Long	Name	Country
7.4622	151.8433	Chuuk International Airport, Micronesia	Micronesia
6.9853	158.2091	Pohnpei International Airport, Micronesia	Micronesia
-9.4275	160.0458	Honiara International Airport	Soloman Islands
5.3530	162.9563	Kosrae International Airport, Micronesia	Micronesia
35.7332	139.3418	Yokota Air Force Base	Japan

Figure 12. LOB Selections for Demand Experiment 1

The supply use rates for this experiment were selected to provide an additional level of analysis. Based on the equation presented in the overview section, we would expect the demand for 2 LOBs using 4 supplies per hour to be the same as 4 LOBs using 2 supplies per hour. The experiment increases the supply use variable in increments of 2 to allow for the analysis of various supply use rates based on the demand at each individual LOB and the number of LOBs available. Finally, the results were analyzed by determining the minimum number of aircraft required for 90% of the aircraft to complete the simulation (reach 360 hours simulation time without a “stop” event occurring indicating a shortfall). If an iteration did not reach the 90% minimum, a plot point was not included on the chart. This indicates that for the 4 and 5 LOB configurations, more than 45 aircraft would be required to meet the demand. The minimum number of aircraft required to complete each configuration was gathered and the results are presented in Figure 13.

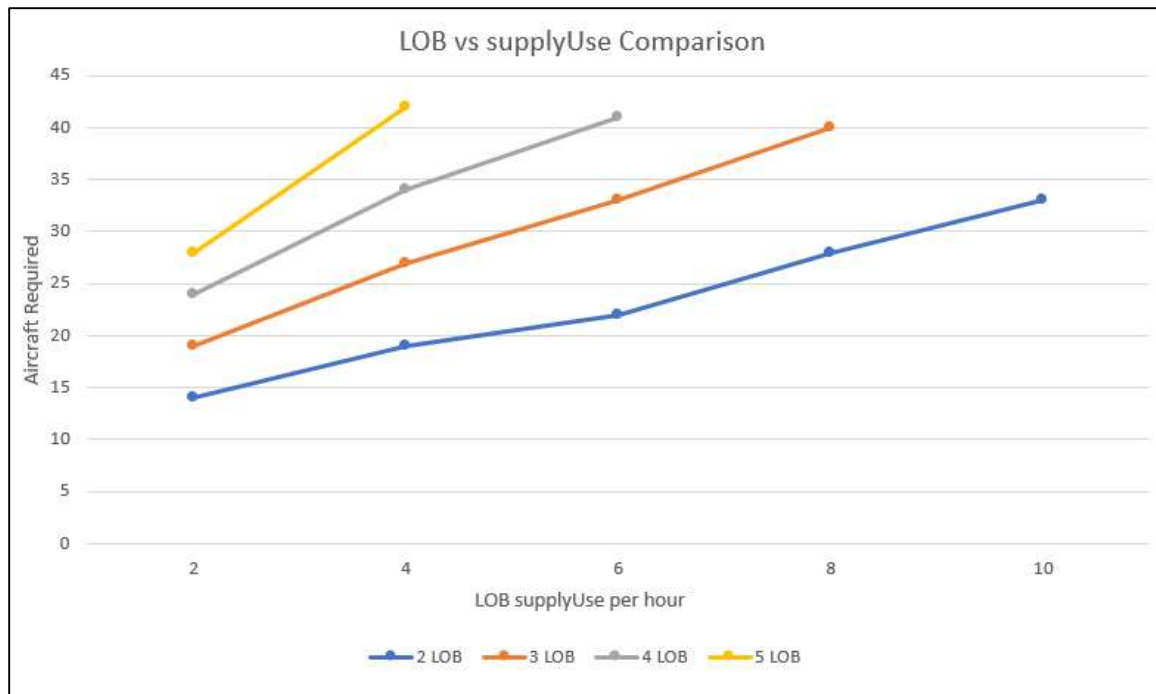


Figure 13. Demand Experiment 1 Results

The chart in Figure 13 indicates that, as expected, an increase in supply use has a multiplying effect on aircraft required based on the number of LOBs in use. This can be seen visually through the approximate slope of the lines. It also indicates that each additional LOB has a relatively set number of additional aircraft required (for a given supplyUse). However, the relationship between the number of LOBs and the supply use rate requires further analysis. When we compare the LOB/supplyUse configurations that should be “equal”, the results do not indicate this result. Instead, the results are skewed, with the lower number of LOB configurations consistently requiring less aircraft. These relationships are indicated by adding arrows to the same chart, replicated in Figure 14. This suggests that a lower number of LOBs is able to achieve greater efficiency and better utilize the additional aircraft in the simulation.

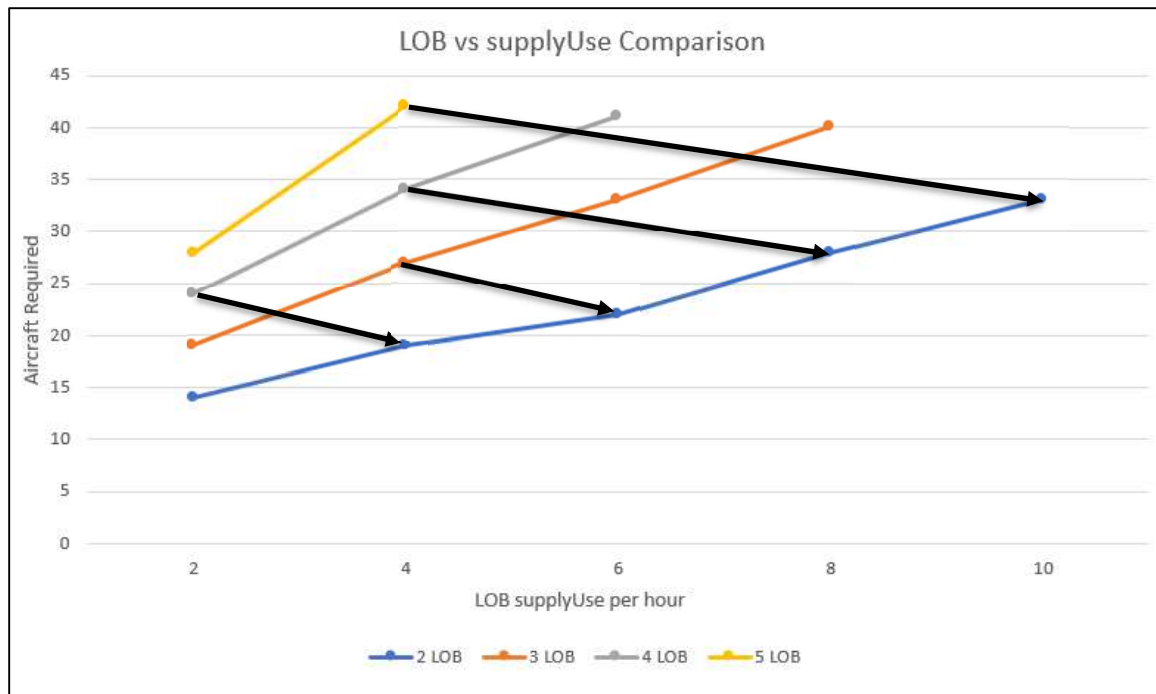


Figure 14. Demand Experiment 1 Additional Analysis

The second demand analysis experiment was designed to understand the relationship between FARP demand and LOB demand. The ratio between the “expected” number of aircraft based on the equation described in the overview section and the actual number of aircraft required for a given configuration to meet a 90% simulation success rate (based on the number of iterations reaching 360 hours) provides one method of parsing this data. For this experiment, a number (45 different configurations) of simulations were run with a variety of supplyUse and FARPdemand selections. SupplyUse ranges were bound within values of 2 to 10 per hour and FARPdemand varied between 0.5 and 4. Additionally, the number of LOBs (2-3) and FARPs (4-12) were varied during the configurations. The resulting configurations were then categorized as “supplyUse weighted”, indicating that the preponderance of demand was weighted towards the LOBs, or “FARPdemand weighted”, indicating that the preponderance of

demand was weighted towards the FARPs. One datapoint was not weighted to either category and was therefore included in both. The ratio of “expected” missions, based on the equation in the overview section, and the required number of aircraft were then plotted and a linear trendline was developed to determine the relationship between the between the LOB demand and the FARP demand. The LOB demand dataset regression resulted in an adjusted R^2 of 0.98038 and the FARP demand dataset resulted in an adjusted R^2 of 0.95904, indicating that a linear relationship can describe the data. The resulting dataset and trendlines are shown in Figure 15.

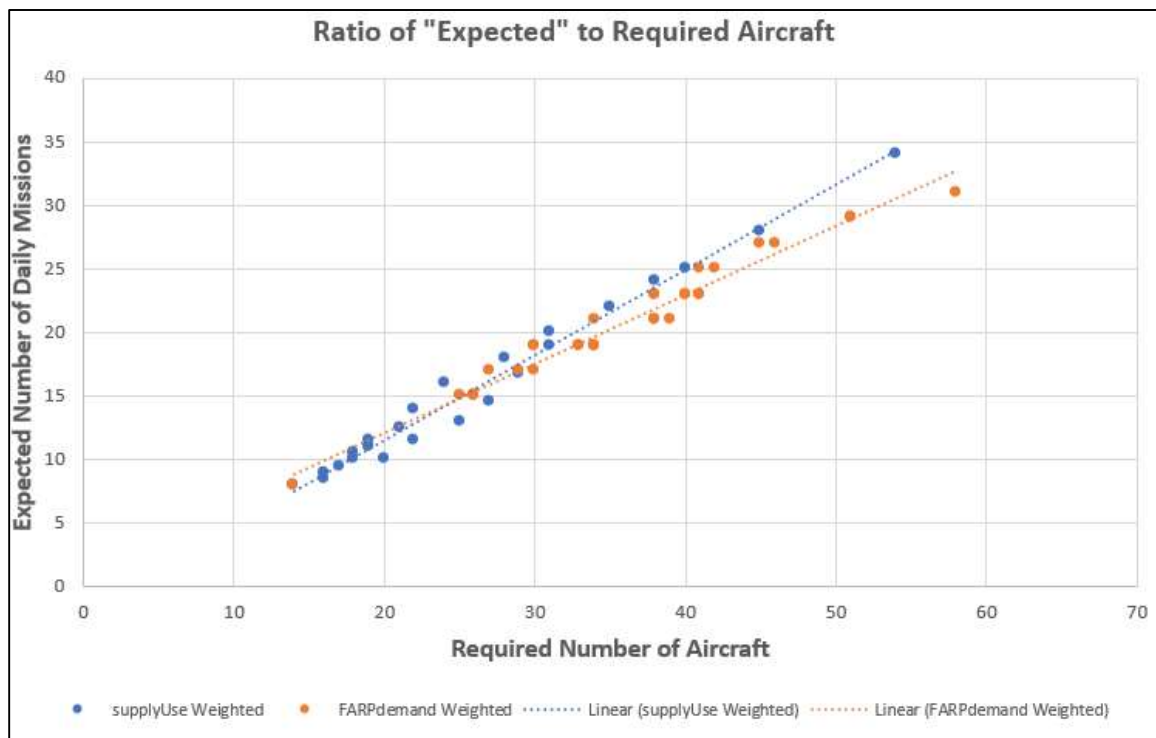


Figure 15. Demand Experiment 2 Dataset

This indicates that with some variance, the relationship between the number of LOBs, number of FARPs, and associated demand inputs is roughly linear (when controlled for distance). However, this dataset does not include a high variation in the number of LOBs and therefore does not negate the results of the first demand experiment.

Instead, we see that the ratio of the expected missions to the aircraft required varies depending on whether the configuration is more weighted towards the FARP demand or the LOB demand. For a given “expected demand”, the amount of that demand driven by the FARPs requires additional aircraft. This is most likely due to the impact that FARP demand has on the entire logistics network. When a FARP requires a mission, it can drive an additional mission from the MOB to LOB as well as the mission required from the LOB to the FARP. Therefore, a FARP demand that is “equal” to a LOB demand has a larger effect on the overall aircraft requirement.

The third demand experiment was designed to analyze the relationships between four configurations of LOBs/FARPs. Two LOBs and 4 FARPs were selected as the “baseline” group for the experiment. Then these LOBs and FARPs were cloned on subsequent experiments to double the available number of LOBs and FARPs as required without an impact due to changing distances. This provided groupings of 2x LOBs/4x FARPs, 2x LOBs/8x FARPs, 4x LOBs/4x FARPs, and 4x LOBs/8x FARPs. Next, the supplyUse and FARPdemand variables were manipulated for each experiment to “equalize” the demand. When the number of LOBs/FARPs were doubled, the associated demand variable was halved. Finally, these iterations of the simulation were run and successful runs were recorded based on the 90% success rate previously discussed. The results of these iterations are summarized in Figure 16.

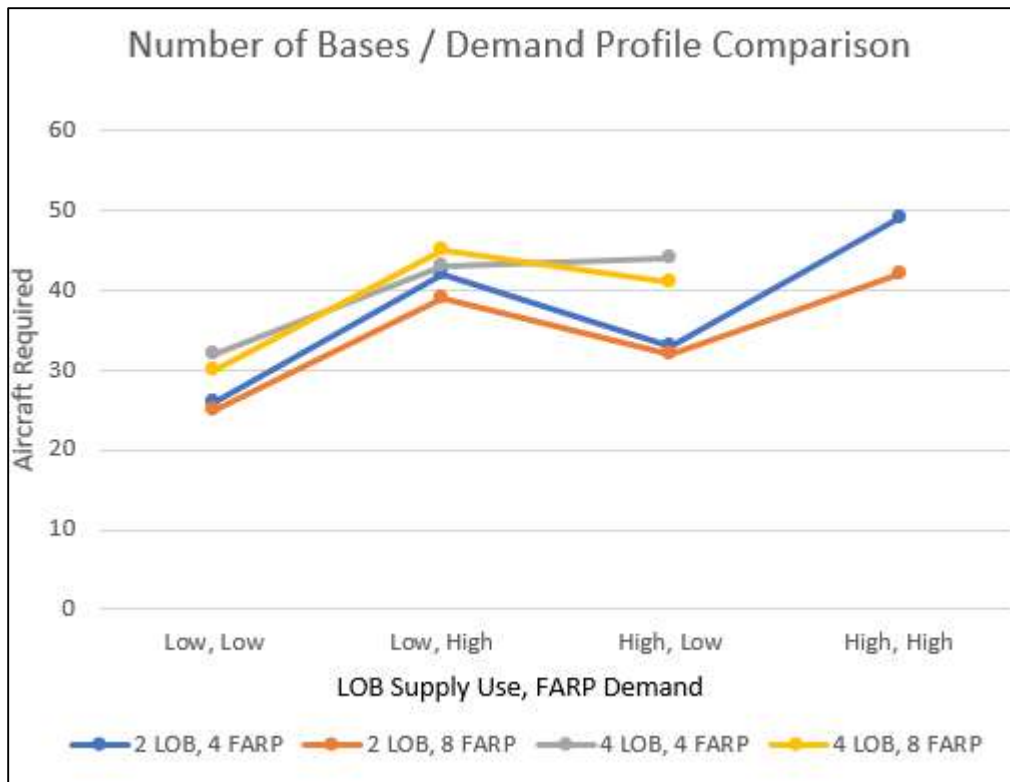


Figure 16. Demand Experiment 3 Results

These results are somewhat mixed and require further analysis. The first conclusion is that in low FARPdemand situations (indicated in the “Low, Low” and “High, Low” categories) there is not a statistically significant difference between the grouping that are expected to be equivalent (4x FARP vs 8x FARP datasets). This was verified through a paired t-test comparing each of these datasets and the resulting statistic did not clear a 90% level of confidence. This indicates that in most low FARP demand situations, the simulation does not indicate a loss or gain due to an increase or decrease in the number of FARPs, assuming the ratio of FARPs/FARPdemand is equal. The data also further validates the results of Demand Experiment 2. The groupings of “Low, High” and “High, Low” results reflect no change in the overall system demand. However, the “Low, High” results reflect a situation where the ratio of FARP demand is

greater, whereas the “High, Low” results reflect a situation where the ratio of LOB demand is greater. In the higher demand FARP situations, more aircraft are required to complete the simulation iterations. Finally, the data suggests that as the differences in the number of bases and demand signals exacerbates the differences previously highlights. This can be seen through the increased slope of the final dataset (showing the highest demand situation possible).

Overall, the system demand is complicated and shows more variability than the data for the distance parameters. FARP demand has a more significant impact on the number of aircraft required to support the distributed basing network. This is likely because the FARP demand requires an aircraft to move “further” in the system (possibly generating two missions). Additionally, an increase in the number of LOBs decreases the efficiency of the network and requires additional aircraft to support the additional bases. In contrast, there is no significant effect on the number of FARPs, assuming that the overall FARP demand (represented by $\text{FARPdemand} \times \text{number of FARPs}$) is held equal.

Working MOG Experiment Data

The working MOG experiment was designed to determine the effect of various levels of capability to service an aircraft at a LOB on the logistics network. The working MOG asset class represents the ability of a LOB to park an aircraft in an area suitable for upload/download, utilize the correct MHE to conduct the upload/download, and have the MHE manned by properly trained personnel. In reality, the working MOG at the airfield can change during different times of day due to manning or equipment shortages. In the simulation, this capability is simply represented through an asset pool, represented by the

“working_MOG” asset class. Each LOB has a designated number of working_MOG assets available in the asset pool. When an aircraft is being uploaded or downloaded, these assets are seized from the pool and utilized. When the upload/download is complete, the asset is returned to the pool. Therefore, in the simulation a working MOG of 1 represents a 24-hour working MOG of 1 at the LOB.

This experiment varies the working MOG value at the LOBs between a working MOG of 1-5. A working MOG of 1 represents the most restrictive scenario the simulation is capable of reproducing. A working MOG of 5 was utilized because in most configurations, the maximum MOG utilization did not exceed this value for a significant amount of time. Therefore, the range of working MOG should represent the most restrictive and least restrictive MOGs for the LOB configurations. In each of the configurations, the same 2 LOBs and 4 FARPs were used. The experiment was run three separate times, adjusting the supplyUse and FARPdemand variables to determine if there was a significant relationship between working MOG and the demand signals.

The experiment results were documented as 2D histograms across a number of available aircraft on the x-axis, and the simulation stop or completion time on the y-axis. The density of the results is represented by a darker color on the histograms, and variability of the results is seen in the vertical spread for a given value for the number of aircraft available. The results of the 2 supplyUse/3 FARPdemand iterations are depicted in Figure 17 to illustrate how the histograms can allow for further analysis.

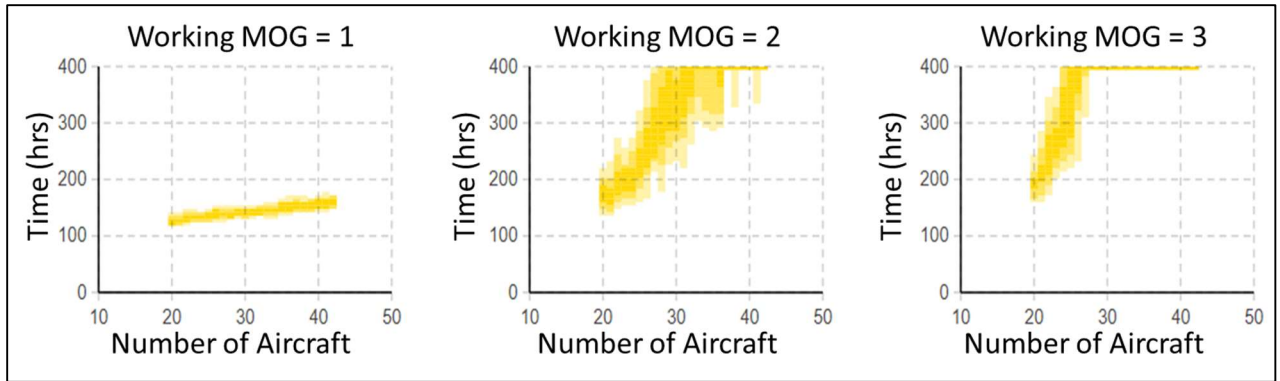


Figure 17. Working MOG Histograms

Figure 17 the same configuration of variables in the simulation, with only the working MOG increasing between simulation runs (from a working MOG of one to a working MOG of three). The results indicate that for a highly restrictive working MOG, increasing the number of aircraft available has a minimal effect on the success of the configuration. In this sense, the working MOG serves as a bottleneck and cannot be overcome. As the working MOG increases, the likelihood of success also increases. Increasing the working MOG value higher than three had minimal effect on the results, suggesting that the peak utilization rate rarely went above 3 in this configuration.

Although only one configuration of variables is depicted in Figure 17, multiple configurations were analyzed. The takeaway from the working MOG experiment was that a lower working MOG results in higher variability in outcomes. Also, in higher demand situations, a lower working MOG leads to a decrease in the likelihood of success. With each successive increase in working MOG, the number of aircraft required decreases and the variability in the outcomes is reduced. The working MOG appears to operate independent of the different LOB/FARP demands and is only affected by the

overall demand. These trends discussed hold true regardless of the supplyUse rate, FARPdemand, or number of locations in use.

This data suggests that the working MOG at a LOB can serve to decrease the efficiency of the system, at times having a significant enough effect to cause mission failure. The variability in the outcomes for the scenarios with a working MOG value of 2 suggests that the demand for upload/download is highly varied in this simulation. If the demand were more evenly distributed, we would expect to see less variation and would be able to better determine the “true” requirement. Instead, the working MOG in the system must be increased to be able to handle the peak demands and accept the inefficiency of the working MOG assets being under-utilized at other points in time.

Disruption Experiment Overview

The disruption experiments were designed to assess the impact of a disruption to one or more LOBs on the overall effectiveness of the distributed basing network. Both disruption experiments employ a similar structure. The distributed basing network consists of 4 FARPs, between 3-8 LOBs, and has fixed inputs for the supplyUse and FARPdemand variables. In the experiments either the rate of disruption or the length of time a LOB spends disrupted is varied. The first iteration of each experiment sets the length/rate of disruption to 0, allowing this iteration to be a baseline “best case scenario” for the configuration. Then, the rate or length of disruption is increased in each additional iteration. This process was then repeated for subsequent numbers of LOBs until all 6 LOB configurations were completed. Due to the high variability of the data, the total length of time allotted for the simulation was increased to 720 hours (double the

previous experiments). Due to this increase, the minimum number of aircraft for the configuration to be deemed successful was determined when the mean length of time for the simulation was at least 2 standard deviations above 360 hours. This would indicate a situation where approximately 97.5% of the iterations of that aircraft configuration would be expected to reach 360 hours.

During the length of disruption variations, the rate of disruption is set at once per day. The length of disruption varies between 0 and 48 hours in increments of 12. During the rate of disruption variations, the disrupt length is set at 12 hours and the rate is increased from 0 to 4 events per day. These increments normalize the expected number of LOBs disrupted at a given time. If one LOB is disrupted and the disruption lasts for 48 hours, the total length of disruption is comparable to have 4 LOBs disrupted for 12 hours each. This allows for analysis not only of the effect of the rate/time of disruption, but for comparison across the “comparable” sets of data.

The disruption experiments data is first presented in the raw 2D histogram form. These histograms were selected to show the broad range of outcomes and illustrate the trends between the configurations. The baseline “no disruption data” is on the left, and as the histogramss move to the right the data shows the effect of increasing the length/rate of disruption. The data shows the length of time of the simulations on the y-axis and the number of aircraft per iteration on the x-axis. The 3-5 LOB scenarios used 20-50 aircraft and the 6-8 LOB scenarios used 30-60 aircraft.

Disruption Experiment Data

The first experiment that this study will analyze is the Disruption Length of Time experiment. The variable of interest in this experiment is the length of the disruption to a LOB when a disrupt event occurs. This length varied during the simulations from 0 to 48 hours. Selected histogram results of the 4 LOB and 8 LOB configurations across a range of disrupt length values are presented in Figure 18.

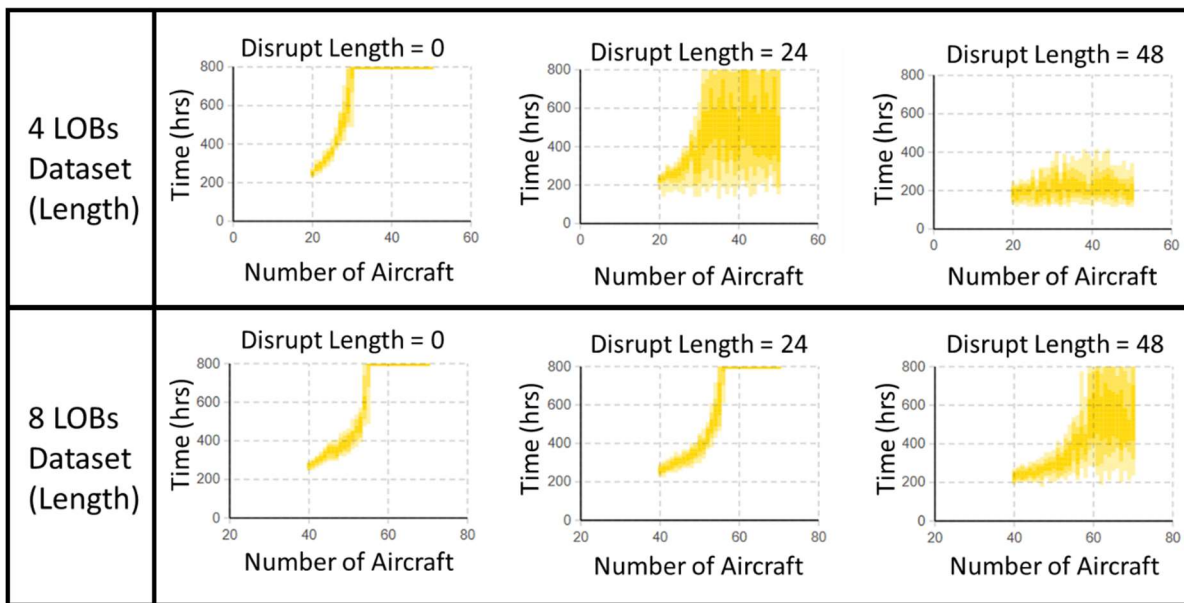


Figure 18. Disruption Length of Time Histograms

The baseline scenario for a configuration is the “zero disruption” graphic. This is how the iterations would distribute based solely on the supply needs of the bases with no enemy attacks. As the length of the disruption increases, we see two trends. First, as the length of disruption increases, the success rate for the simulation is reduced (fewer iterations reach the maximum y-axis value) and the variability of the outcomes increases significantly (wider vertical spread along the y-axis). When the length of disruption increases to the point where there is a reasonable chance of all LOBs being disrupted, the

simulation usually results in failure. This is seen most acutely in the upper right graph, illustrating 4 LOBs under threat of a 48-hour length of disruption. However, the second trend visible in the data is that as the number of LOBs increases, the likelihood of success increases. This is seen by comparing the 4 LOB graphs to the 8 LOB graphs shown directly below them. This suggests that although having more LOBs available requires more resources, it does increase the resiliency of the network. This is also visible when we compare the data showing the minimum number of aircraft required to support a given scenario. This data is shown in Figure 19.

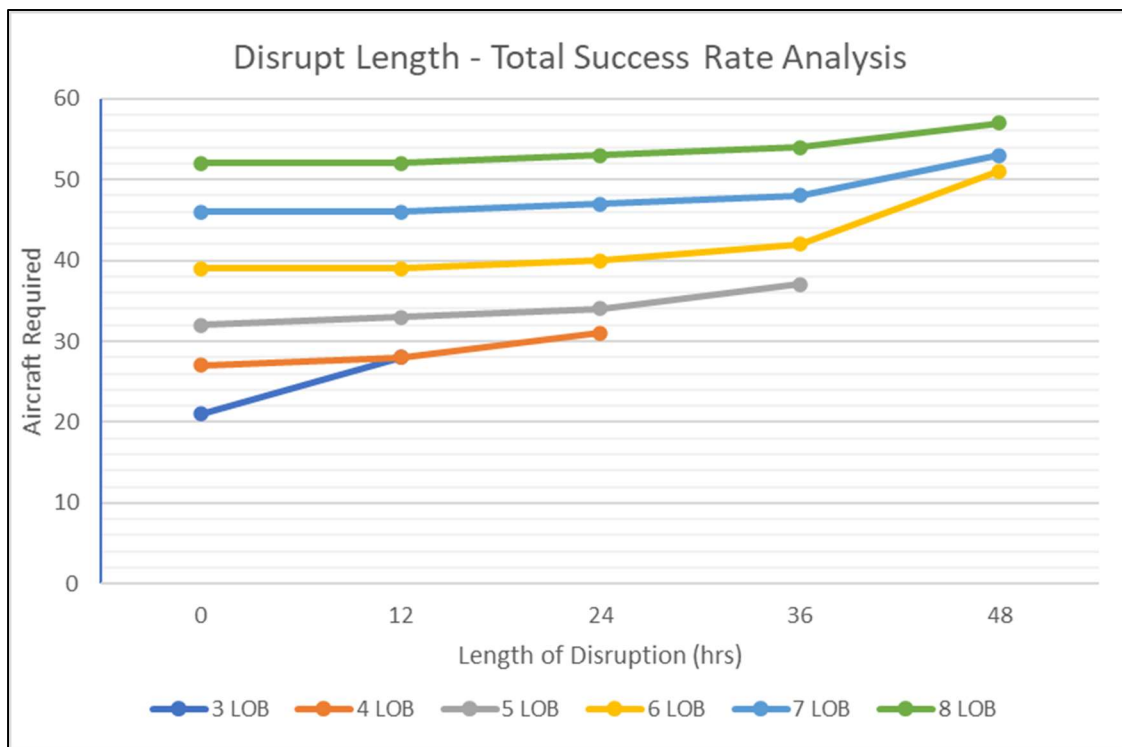


Figure 19. Disruption Length of Time Minimum Successful Configuration Results

Figure 19 depicts the minimum number of aircraft required (y-axis) based on the length of time the LOB spent disrupted per disruption event (x-axis). The results for each LOB configuration are shown as points and the trends are tracked via the colored lines

between the points. Therefore, if we follow the line from left to right, we can track the result of each 12-hour increase of disruption length on the aircraft requirements for that LOB configuration (the number of LOBs used in that experiment). Additionally, we can compare the different configurations to draw broad conclusions.

This data matches the conclusions from the histogram data, but makes it easier to identify trends in the data. Here, it is evident that in low LOB configurations, it is frequently impossible for aircraft to meet the success criteria. This is shown by the low LOB configurations missing datapoints, indicating that the configuration never reached the success criteria. In the higher LOB configurations, the data shows that no additional aircraft may be required if the length of disruption is sufficiently low. Finally, this data shows that even with a minimum successful LOB configuration (6 LOBs based on this dataset), high lengths of disruption lead to additional aircraft requirements. At times, this additional requirement nearly matched the levels required by adding another base entirely. Overall, this data shows that the length of a disruption has a significant effect on the distributed basing network, but that increasing the number of LOBs can lessen this effect.

The second experiment that this study will analyze is the Disruption Rate experiment. The variable of interest in this experiment is the rate at which a disruption event occurs. This rate varied during the simulations from 0 to 4 events per day. Selected histogram graphs for the 4 and 8 LOB datasets are presented in Figure 20.

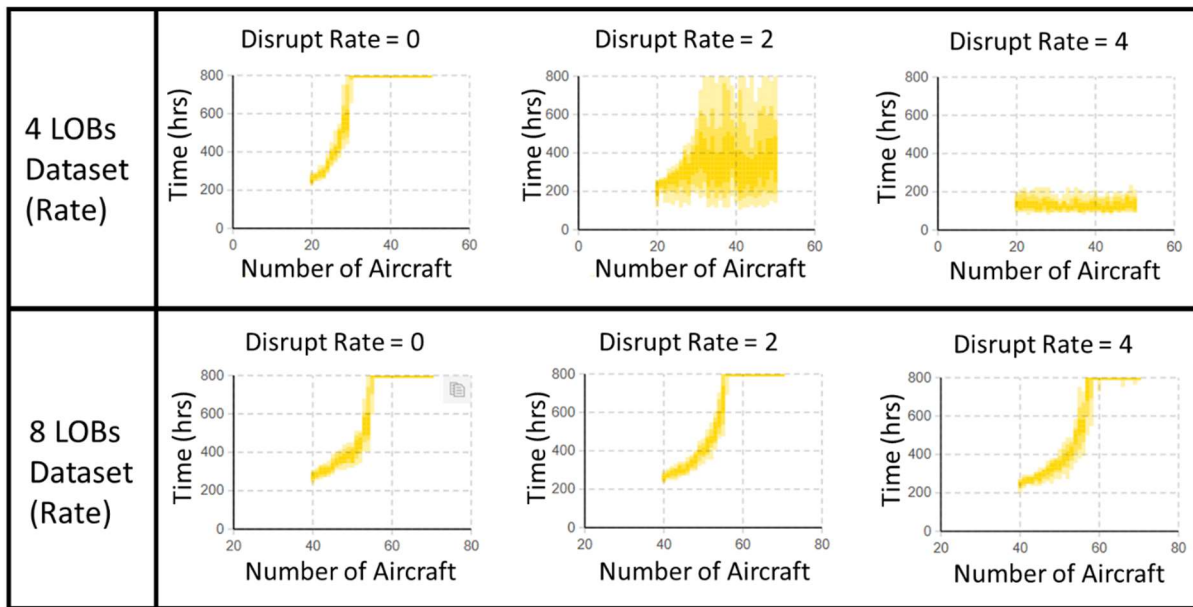


Figure 20. Disruption Rate Histograms

The data presented shows similar trends to the length of disruption experiment. As the number of disruption events that occur per day increase, more variability is shown in the results and more aircraft are required. This effect is also lessened as the number of LOBs are increased. However, the data also suggests two differences. The first difference is that for the low LOB configurations (for example, the 4 LOB configuration depicted), failure tended to occur early than in the length of time experiments. This may be attributed to the cumulative time it takes for the length of time experiments to reach maximum disruption. The second difference is that for the higher LOB configurations (for example, the 8 LOB configuration depicted) we see significantly less variability in the outcomes. The minimum number of aircraft required to support a configuration displays a similar trends to the data from the length of time experiments and is presented in Figure 21.

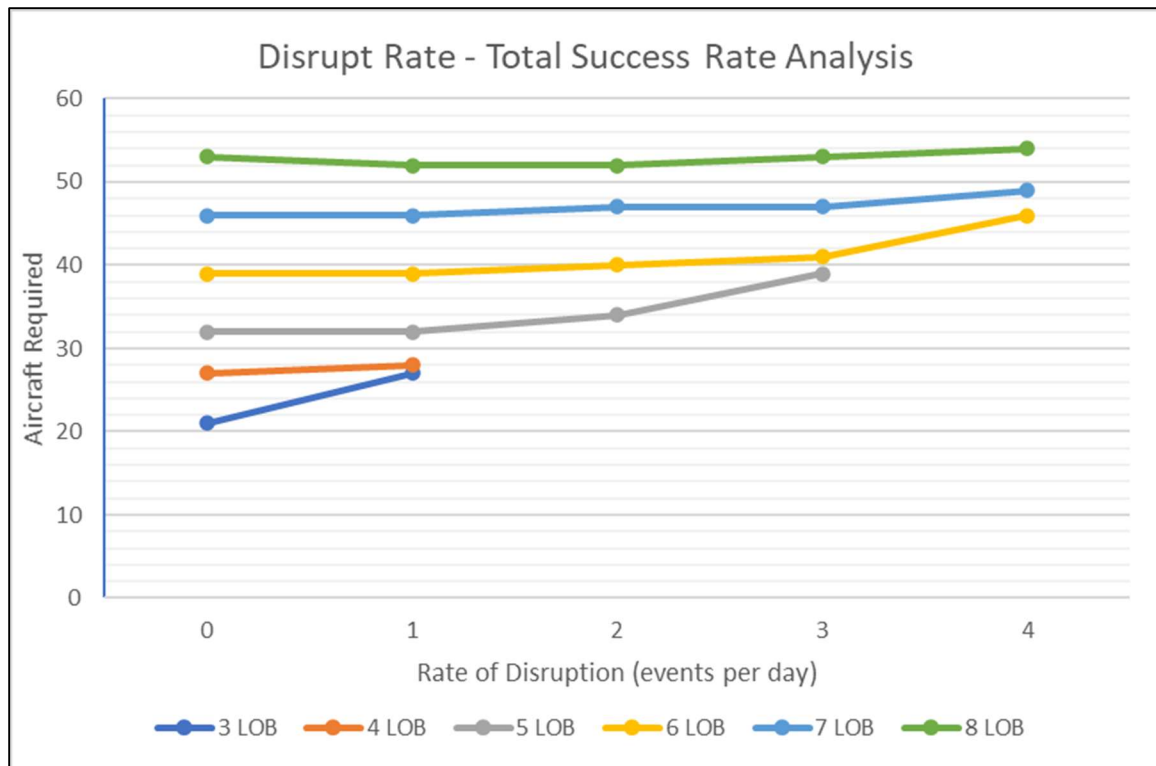


Figure 21. Disruption Rate Minimum Successful Configuration Results

Figure 21 depicts the minimum number of aircraft required (y-axis) based on the rate of disruption events occurring per day (x-axis). Otherwise, the data reads similarly to Figure 19. The data shows that increasing the number of disruption events per day has a negative effect on the logistics network. It also shows that as the effect becomes more significant, it requires more aircraft to support the given configuration. This effect is shown by the relative slope of the lines connecting the data points. We can see that the effect exists for all configurations, but that it is lessened for the configurations with more LOBs. Once again, adding additional LOBs to the distributed basing network increases the resiliency of the network and reduces the negative effects of the disruption event.

The length of disruption and rate of disruption data show similar trends, but without compiling the data and presenting it together, it is difficult to compare the

significance of the effect of the two variables (rate and length of disruption). The compiled Minimum Success Rate table is shown in Figure 22.

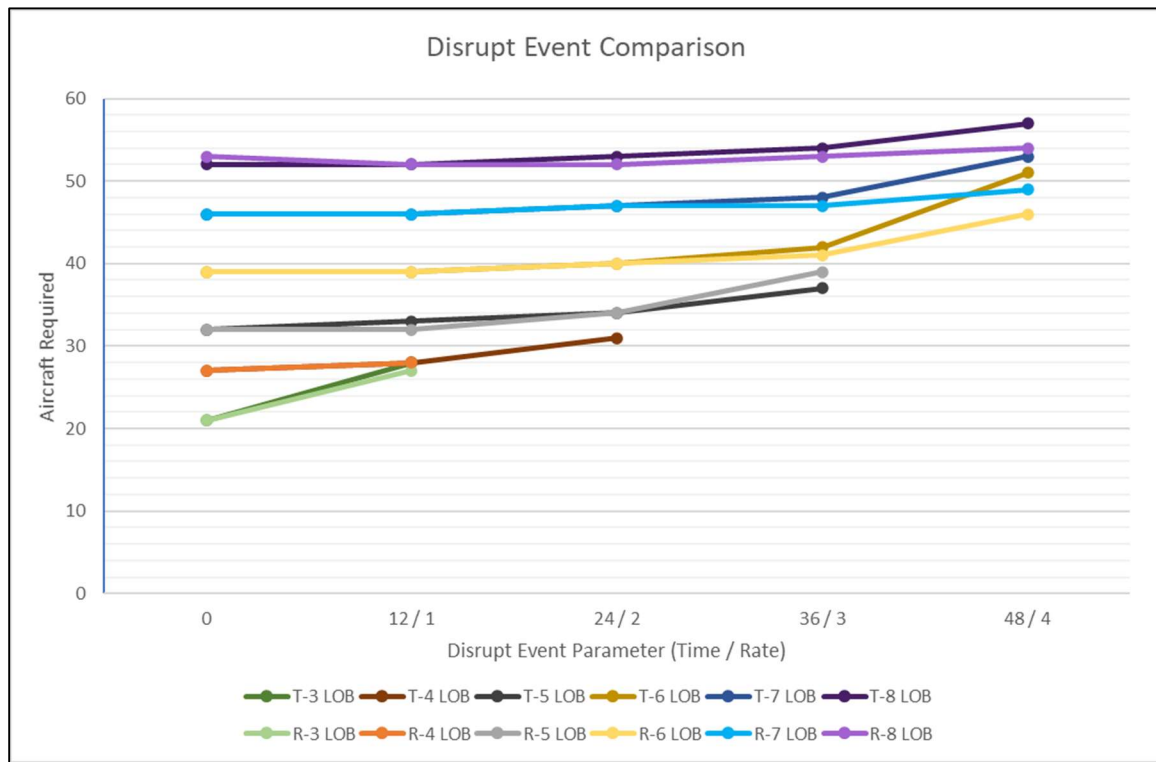


Figure 22. Disruption Event Success Rate Comparison (Length of Time & Rate)

This data is the same data as Figures 19 and 21, but is compiled on one normalized graph to illustrate the trends between the two experiments. The length of time LOB data is shown with the prefix “T” and the rate of disruption LOB data is shown with the prefix “R”. As we would expect, the first datapoint showing zero disruptions matches in both scenarios. Additionally, with minor disruptions there are minor differences in the outcomes based on the rate and length of disruption. However, as the severity of the disruption increases in either rate or length, we see trends emerge. The longer a LOB spends in the disrupted state, the more significant the effect on the logistics network. This effect is also seen when comparing the histograms from the length and

rate experiments. For ease of comparison, the 8 LOB configuration disruption length of time and rate of disruption results are shown in Figure 23.

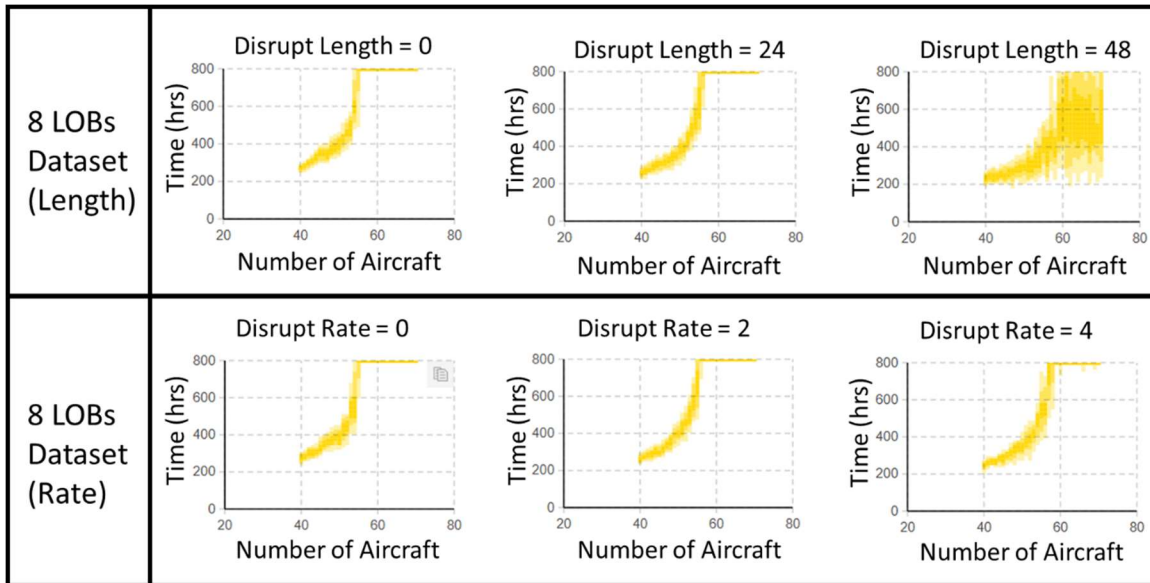


Figure 23. Disruption Results Comparison for 8 LOB Datasets

This data matches the trend shown in Figure 22. In the lower rates and length of disruptions tests, the 8 LOB configuration is effective. However, as the length of the disruption increases, the data shows a wide range of potential outcomes emerge, shown in the top right graph. For a similarly severe rate of disruption, the 8 LOB configuration is much more successful and shows a much tighter range of outcomes. The length of time a LOB spends disrupted has a greater negative effect than the rate of disruption events.

Overall Results and Implications

The experiments and data presented in this section can be grouped into four categories: distance, demand, working MOG, and disruption. This section will briefly summarize the results of the experiments within these four categories. It will also highlight instances where the results from one category would have an impact on the

implementation of a result from a separate category. Furthermore, this section will provide real-world implications for the results that have been gathered.

The results of the distance experiments show that an increase in distance between the MOB and the mission locations results in more aircraft being required to support the logistics network. Additionally, the results suggest that the distance from the MOB to a LOB has a greater effect on the number of aircraft than the distance from the LOB to a FARP. If possible, planners should prioritize potential basing locations that minimize round trip distance and proximity to the nearest MOB.

The demand results suggest that there is minimal effect on the overall logistics network whether one FARP is used more often or multiple FARPs are employed (assuming the total mission rate is the same). In contrast, the LOB data suggests that economies of scale can occur by consolidating the number of LOBs to improve the efficiency of the network. If the consolidation of LOBs also results in more efficient supply use, these gains would be further increased. The results also suggest that rate of FARP missions is the primary demand driver for aircraft moving through the system. As FARP mission demand increases, proportionally more aircraft are required. Although decreasing the LOB supply use rate would reduce aircraft requirements, additional missions may be required to position aircraft for FARP missions, even if there is not cargo that needs to be moved to a LOB. This could be mitigated by basing the aircraft at a LOB rather than expecting a return to the MOB.

The working MOG experiment shows that the working MOG is a bottleneck in the system. If the working MOG is too low, it is not possible to sustain the logistics network. Improving the working MOG has a dramatic effect on the likelihood of success

for the transportation network and significantly reduces the number of aircraft required to support the network. Improving the working MOG also reduces variability in the possible outcomes.

The two disruption parameters analyzed were the rate of disruption and the length of time that a LOB spends disrupted. An increase in either of these parameters resulted in a negative impact on the logistics network. The negative impact is lessened when more LOBs are available, but the number of aircraft to support the distributed basing network increases as the number of LOBs increases. The most significant factor leading to the failure of a network when disrupted is the length of time that a LOB spends disrupted. When the LOB is able to recover quickly from a disruption, the network is able to handle a higher disruption rate. The optimum configuration to manage frequent disruptions is a large network that is able to recover quickly from a disruption, but this may require a significant increase in the number of aircraft required to support the network.

Research and Investigative Questions Answered

This study set out to determine the impacts to the Mobility Air Forces in the implementation of a distributed basing and logistics network in the Pacific theater. The impacts to the Mobility Air Forces was quantified by analyzing the number of aircraft required for a given configuration of bases. Additionally, the ground support required to ensure mission success was assessed using the working_MOG variable. The results of this study indicate the impacts of this network on the Mobility Air Forces.

The study sought to provide more depth on the analysis of the research question through four investigative questions. The investigate questions and summarized answer are presented below.

1. What is the relationship between the number and type of bases in theater and the aircraft required to supply these bases?

There is a positive linear relationship between the number of bases and the number of aircraft required to support the bases. The number of aircraft increases based on the number of bases and the demand requirement for the bases. Additionally, the type of base plays a role in determining the overall number of aircraft. The number of FARPs (demand nodes) and associated demand has a more significant effect on the number of aircraft required. An increase in the number of LOBs (transshipment nodes) increases the number of aircraft required. For a given rate of LOB supply use, utilizing less LOBs is more efficient and requires less aircraft.

2. What impact, if any, does a disruption to a node have on the number of aircraft required to support the distributed network?

The disruption of a LOB has a significant effect on the operation of the distributed network. The severity of the disruption can greatly increase the number of aircraft required or result in no chance of mission success. This effect is lessened when a larger number of LOBs are available. Additionally, the network is less affected if the LOBs that are disrupted are able to recover more quickly.

3. What are the critical variables in a distributed logistics model that effect sustainment and increase or decrease the crew force workload, for example:

aircraft cargo capability, distance between distributed bases, support personnel required?

The critical variables in this distributed logistics model are the distance between the bases (nodes), the demand at each node, the support personnel available (represented by working MOG), and the rate and length of time the LOBs spend disrupted. This study did not address aircraft cargo capability or the impact on associated aircrews.

4. How sensitive is the model to changes in assets available, demand, and number of aircraft available?

The model is sensitive to changing inputs and the study was able to quantify and identify trends associated with the changing inputs and configurations. The data presented in this section summarizes the results of the sensitivity analysis.

Summary

This section expanded on the experiments discussed in Chapter III and presented the data gathered from the nine planned experiments listed in Table 1. Through the exploration and analysis of this data, the research question was successfully answered. Additionally, the experiments were effective in answering the four investigative questions. The results of this chapter indicate the effectiveness of simulation and modeling as a method for analyzing possible strategic concepts and paradigms for the Air Force.

V. Conclusions and Recommendations

Chapter Overview

This chapter will discuss the overall conclusions of adaptive basing simulation and research. Next, it will identify the impact and the research and highlight important conclusions. It will then provide recommendations for action. Finally, it will conclude with recommendations for additional research.

Conclusions of Research

After the results of the experiments were analyzed, four categories of analysis were identified. These categories summarize the conclusions from across the research experiments to develop potential outcomes and implications for the future development of the adaptive basing and distributed basing models. These categories include:

1. Size and shape of the logistics network
2. Effects of the demand inputs
3. Working MOG considerations
4. Disruption effects and implications

Size and Shape of the Logistics Network

The size and shape of the logistics network required to support operations in the Pacific theater is likely to conform to one of two broad categories. The first category is a larger number of smaller dispersed bases. The second category is a smaller number of more consolidated and larger bases. This section will discuss the implications of the research on either of these paradigms.

Utilizing a larger number of smaller bases has a number of advantages. This configuration is inherently more resilient and less likely to be fully disrupted regardless of the length of time of the disruptions or the rate which disruptions occur. Furthermore, by utilizing more LOBs, an adversary is required to target more locations. This may reduce the effectiveness of enemy attacks on the locations. A smaller base footprint also implies that the supply use rate for the base would be reduced, but there is not currently any data that would indicate how large of a reduction would occur.

There are also disadvantages associated with this configuration. A larger number of bases that are further dispersed implies that inefficiencies will exist due to a larger distance between LOBs as well as the bases being unable to consolidate efforts and achieve economies of scale. This indicates that a more dispersed set of bases is likely to require more aircraft to support the locations unless the supply use rate for those locations is dramatically reduced. Also, it will likely require more ground support personnel and equipment due to the increased number of operating locations.

There are also a number of advantages to a consolidated basing network. The first advantage is that this configuration is inherently more efficient. Less ground handling personnel and MHE will be required due to the efficiencies gained by increasing the utilization of the assets at a smaller number of locations. This also implies that less aircraft will be required to support the locations as the configuration has been shown to be more efficient through the data. Due to the smaller number of LOBs required to create this configuration, optimal locations can be selected to reduce the overall distance of the logistics network, further reducing the aircraft requirement.

The biggest shortfall of this basing configuration is the difficulty in recovering from disruptions. All configurations with a small number of LOBs showed a weakness to disruption. If the adversary is able to remove all available transshipment nodes, the logistics network shuts down entirely and there is a high likelihood that aircraft will be diverted or forced into unsafe landing or ditching situations. This scenario is more likely in a consolidated configuration unless the bases are highly resilient and able to recover quickly. An additional drawback of this configuration is that large operating locations become more desirable targets for the enemy. It is likely that consolidated bases would require more equipment to provide self-defense and keep the locations operational.

Effects of the Demand Inputs

The demand inputs at the FARPs and the LOBs are the primary drivers of aircraft in the system. If demand did not exist, no aircraft would be required. However, there will always be some level of demand and it is incumbent on the Air Force to understand the implications of the demand signals. The primary mission driver is the FARP demand. A higher FARP demand increases the amount of aircraft required in the system, the number of LOBs required to support those FARPs effectively, and increased working MOG capacity due to the increased throughput at the transshipment nodes. However, the LOB supply use (LOB demand) is also an important driver of aircraft in the system. If the LOB supply use rate is higher, indicating a less self-sufficient base, more aircraft are required. It is highly likely that the Air Force would be employed in a scenario requiring quick action. In this situation, the FARP demand is dictated by mission requirements. However, the Air Force can impact the LOB supply use rate through pre-positioning of

materiel, more efficient processes, or working towards a more self-sufficient force. These have impacts on the LOB demand and can reduce the requirements of the logistics supply chain.

It is also important to note here that the aircraft size in the simulation was not necessarily taken into consideration in terms of utilization. Although a C-17 aircraft in the simulation was capable of carrying 0-16 “units” of supply, this does not necessarily correlate to an amount required to resupply a location. Instead, the relationship between these supply units and the aircraft used should be considered. The C-17 aircraft was selected for use due to the ability of the aircraft to cover the large distances required in the Pacific theater. If half of a C-17 was required, an entire aircraft was still sent. In some LOB configurations it may be possible for one aircraft to conduct two missions in a single duty-day, but this was not possible in the simulation. The actual amount of resupply required for a location requires additional analysis and if the amount required is significantly less than a C-17 load, it may make more sense to modify an existing smaller aircraft to meet this requirement.

Working MOG Considerations

The working MOG at a LOB is the bottleneck in the logistics network. A working MOG lower than the number of aircraft that require upload/download at a given time serves only to delay the flow of resources through the network. This inefficiency can be overcome through additional aircraft (resources), but this is not the most optimal way to solve this problem. Realistically, two steps can be taken to reduce the effects of a below-desired working MOG. The first is to allocate more resources to the MHE and to

the personnel required to upload/download aircraft. This may not be the most efficient solution, but it increases the redundancy in the system and provides opportunity for locations to “surge” in capacity as required. The second option is to improve the scheduling of aircraft to “level” the demand as compared to the working MOG. This is already conducted by mission planners, but this type of planning was not possible in the simulation. However, it should be noted that leveling the demand incurs some inefficiencies as aircraft may be delayed to avoid being above the working MOG at a field. Currently, these inefficiencies can be accepted by mission planners because the impact is low and can be mitigated.

Disruption Effects and Implications

The disruption of a transshipment node has significant effects on the overall transportation network. The longer the node is offline, the more likely it becomes that a LOB will experience a supply shortfall. Although it would be possible to conduct emergency resupply to these locations via airdrop, this is not an optimal solution. This research suggests that recovering quickly at a LOB after a disruption should be prioritized. The first factor to take into consideration is what types of disruptions would require significant downtime. Any attack is likely to disrupt operations during the battle damage assessment. However, if the attack does not impact critical infrastructure the effects are likely to be minimal. Conversely, if critical infrastructure is impacted (fuel tanks, runways, etc.), it is more likely that the disruption will have follow-on effects. This research suggests that there are significantly reduced effects even if attacks occur frequently, assuming that the LOB is able to get back to operational status quickly.

Further analysis of what constitutes a disruption event should be discussed. A loss of critical infrastructure to generate sorties has the largest impact on the logistics network. This infrastructure likely includes but is not limited to runways, fuel storage, weapons storage, MHE, and the aircraft itself. If it is possible to improve the defenses of a location to harden these facilities or reduce the effectiveness of these attacks, this would reduce the rate and length of disruptions. Additionally, if critical infrastructure such as the runway were less critical, it would reduce the effectiveness of enemy attacks. This can be illustrated through an example. If we take a 7'000' runway and an aircraft that requires 5,000' to land, any single crater impact outside the first or last 2,000' of runway would render the runway unusable. If instead the aircraft required 3,000' to land, a single crater cannot make the runway unusable. By focusing on the aircraft rather than the base, it may be possible to develop other methods to improve the resiliency of the air transportation network.

Recommendations for Action

The analysis of the literature review, simulation results, and implications of the results has led to the development of a few recommendations for action. The possible recommendations include:

1. Size and shape of the logistics network
 - a. Determine the real-world requirements associated with increasing the number of bases to develop a distributed basing network.

- b. Quantify the likelihood and severity of potential disruptions to the logistics network in order to determine which of the two network shapes is more likely to succeed.
- c. Identify potential FARP locations that can be used with minimal additional resources.
- d. Identify optimal sites for additional transshipment nodes across the theater based on location.
 - i. Sites should be prioritized based on overall distance and distance from the MOB.
 - ii. Consideration must be given to diplomatic clearances and airspace concerns.

2. Effects of demand inputs

- a. Utilize the expected FARP missions per day to determine a minimum number of FARP locations required.
- b. The rate at which FARPs can be re-used will also drive the overall number of FARPs selected.
- c. Quantify the supply use rates expected at a LOB location of a given size in order to determine which logistics network configuration is more useable.
- d. Utilize the expected supply rates to determine the most effective aircraft to conduct resupply in the network.

3. Working MOG Considerations

- a. Prioritize assets that are flexible and allow working MOG to be scaled up or down as required.
 - b. Determine the likely working MOG needed at a location and ensure that the capability to meet this exists within the force structure.
- 4. Disruption Effects and Implications
 - a. Implement additional training on recovering from a disruption event.
 - b. Prioritize development of systems that allow for rapid recovery after a disruption event.
 - c. If possible, implement technology that prevents or mitigates the effects of a disruption.

Recommendations for Future Research

Analysis of the overall research suggests a number of potential avenues for additional research. The six critical areas for future research are:

1. Analyze and compare measures to reduce disruptions at a transshipment node.
2. Determine the effects of the distributed basing model on lodging, crew rest requirements, and sleep cycles.
3. Quantify the impacts of aircraft maintenance on the distributed basing model and identify ways to mitigate negative effects identified.
4. Analyze the likelihood and extent of adversary disruption capability compared to our ability to mitigate these attacks.
5. Analyze the potential gains or losses due to aircraft size and overall carrying capability cargo capability within the distribute basing model.

6. Research to determine accurate inputs to the FARP mission model and compare the aircraft, cargo, and personnel requirements.

Summary

This research study began with the need for further analysis of concept models proposed by the Air Force to meet the Secretary of Defense's vision of future warfare. It is critical for the military to be able to conduct operations in the face of a near-peer adversary who will likely attempt to prevent operations near their territory. A thorough analysis of the proposed concepts was conducted and the scientific literature was reviewed to determine if a method existed to evaluate these concepts. The literature indicated that although the use of simulation could provide insight concerning the feasibility of the adaptive basing and distributed basing models, this had not been previously accomplished by the military or civilian sector.

AnyLogic was used to develop a simulation that could effectively replicate a variety of distributed basing configurations, ranging from small base networks to a larger distributed basing network. This simulation was then used to conduct a series of experiments to better understand the impacts of a number of variables on the air transportation fleet and logistics network. These experiments indicated significant relationships between the distance between bases, demand signals at the bases, materiel handling equipment availability, and the rate and time of adversary disruptions to the logistics network. The experiments conducted using the software were effective in answering the research and investigative questions proposed by the research study.

Recommended categories for further action were identified based on the results of the research experiments and the insights gained through the use of the simulation. These include possible avenues to implement an appropriately sized network of bases, better manage the demand at individual bases in the network, minimize the impacts of insufficient materiel handling equipment, and mitigate the effects of a disruption to the network. Lastly, future areas for research were identified to further validate and quantify the effects identified in this study.

This research paper suggests that there are multiple ways for the Air Force to overcome the challenges presented by a near-peer adversary. The research also highlights the tradeoffs that will result from choosing one of these models. This fortifies the case for utilizing simulation to better analyze and understand proposed future warfare concepts. As a result, decision makers can be better informed about the risks and potential end states of strategic decisions and the likely impacts these will have at the tactical and operational levels.

Bibliography

- Abdelghany, A., & Abdelghaney, K. (2009). *Modeling Applications in the Airline Industry*. Surrey, England: Ashgate Publishing Limited.
- Aberson, C., Berger, D., Healy, M., Kyle, D., & Romero, V. (2000). Evaluation of an Interactive Tutorial for Teaching the Central Limit Theorem. *Teaching of Psychology*, 289-291.
- Amouzegar, M., McGarvey, R., Tripp, R., Luangkesorn, L., Lang, T., & Roll Jr., C. (2006). *Evaluation of Options for Overseas Combat Support Basing*. Santa Monica, CA: RAND Corporation.
- Banks, J., Carson, J., Nelson, B., & Nicol, D. (2001). *Discrete-event system simulation*. Upper Saddle River, NJ: Prentice Hall.
- Campbell, J., & O'Kelly, M. (2012). Twenty five years of hub location research. *Transportation Science*, vol. 46, no. 2, 153-169.
- Cartenti, A., & Luca, S. (2012). Tactical and strategic planning for a container terminal: modelling issues within a discrete event simulation approach. *Simulation Modeling Practice and Theory*, vol. 21, no. 1, 123-145.
- Chen, B., Cheng, H., & Palen, J. (2012). Integrating mobile agent technology with multi-agent systems for distributed traffic detection and management systems. *Transportation Research Part C: Emerging Technologies*, 17, 1-10.
- Choi, J., Lee, C., & Park, S. (2018). Dantzig–Wolfe decomposition approach to the vehicle assignment problem with demand uncertainty in a hybrid hub-and-spoke network. *Annals of Operations Research* 264, 57-87.
- Cliff, R., Burles, M., Chase, M., Eaton, D., & Pollpeter, K. (2007). *Entering the Dragon's Lair: Chinese Antiaccess Strategies and Their Implications for the United States*. Santa Monica, CA: RAND Corporation.
- Crainic, T., Perboli, G., & Rosano, M. (2017). Simulation of intermodal freight transportation systems: a taxonomy. *European Journal of Operational Research* 270, 401-418.
- Davis, R. (2014). Forward arming and refueling points for fighter aircraft: Power projection in an antiaccess environment. *Air & Space Power Journal*, Sept-Oct 2014, 5-28.

- Defense, U. D. (2012). *Sustaining U.S. Global Leadership: Priorities for 21st Century Defense*. Washington D.C.: Office of the Secretary of Defense.
- Du, M., Jiang, X., Cheng, L., & Zheng, C. (2017). Robust Evaluation for Transportation Network Capacity under Demand Uncertainty. *Journal of Advanced Transportation*, vol 2017, 1-11.
- Gabka, J., Susz, S., & Rosienkiewicz, M. (2016). An Integrated Approach towards Building a Simulation Model Supporting the Management of the Passenger Transportation System. *Logistics & Transport*, no. 4, 39-64.
- Garrow, L. (2009). *Discrete Choice Modeling and Air Travel Demand, Theory and Applications*. Surrey, England: Ashgate Publishing Limited.
- Goldsman, D., Pernet, S., & Kang, K. (2002). *Simulation of Transportation Logistics*. Georgia Institute of Technology: Winter Simulation Conference.
- Hatch, B. (2015). *Optimizing dispersed air operations: A concept to use highways as improvised airfields in a contested environment*. Maxwell AFB, AL: Air University Press.
- Jahangirian, M., Eldabi, T., Naseer, A., Stergioulas, L., & Young, T. (2010). Simulation in manufacturing and business: A review. *European Journal of Operational Research* 203, 1-13.
- Kim, H., & O'Kelly, M. (2009). Reliable p-hub location problems in telecommunication networks. *Geographical Analysis*, no 41, 283-306.
- Kuhnt, S., & Wenzel, S. (2010). Information acquisition for modelling and simulation of logistics networks. *Journal of Simulation* 4, 109-115.
- Latham, J. (2019, October 9). *How to Calculate Distances in Excel*. Retrieved from Contextures: <https://www.contextures.com/excellatitudelongitude.html>
- Lazidis, C. (2016). *Air Parity: Re-Discovering Contested Air Operations*. Maxwell AFB, AL: Air University Press.
- Mahmoudabadi, A. (2014). Developing a Chaotic-Simulation Based Model for Ranking High Selected Network Links in Hazardous Material Transportation. *Modeling and Simulation in Engineering*, vol 2014, 1-8.

- Mastro, O., & Easton, I. (2017). *Risk and Resiliency: China's Emerging Air Base Strike Threat*. Arlington, VA: Project 2049 Institute.
- Mattis, J. (2018). *Summary of the 2018 National Defense Strategy of the United States*. Washington D.C.: Department of Defense.
- Norman, G. (2010). Likert scales, level of measurement, and the "laws" of statistics. *Advances in Health Science Education*.
- Ören, T., & Yilmaz, L. (2009). On the Synergy of Simulation and Agents: An Innovation Paradigm Perspective. *International Journal of Intelligent Control and Systems*, vol. 14, no. 1, 4-19.
- Owen, R. (2017). *Shaping air mobility forces for future relevance*. Maxwell AFB, AL: Air University Press.
- Panel, N. S. (2006). *Report on Simulation-Based Engineering Science: Revolutionizing Engineering Science through Simulation*. Alexandria, VA: NSF Press.
- Priebe, M., Vick, A., Heim, J., & Smith, M. (2019). *Distributed Operations in a Contested Environment*. Santa Monica, CA: RAND Corporation.
- Ragsdale, C. (2004). *Spreadsheet Modeling & Decision Analysis, Fourth Edition*. Mason, OH: Thompson Learning.
- Ran, B., & Boyce, D. (1996). *Modeling Dynamic Transportation Networks: An Intelligent Transportation System Oriented Approach*. Berlin: Springer.
- Rocha, L. (2016). *Dynamics of air transport networks: A review from a complex systems perspective*. Namur, Belgium: Department of Mathematics, University of Namur.
- Santoso, T., Ahmed, S., Goetschalckx, M., & Shapiro, A. (2005). A stochastic programming approach for supply chain network design under uncertainty. *European Journal of Operational Research*, 167, 96-115.
- Sun, X., Wandelt, S., & Cao, X. (2017). On node criticality in air transportation networks. *Networks & Spatial Economics*, 737-761.
- Thomas, B., Amouzegar, M., Costello, R., Guffey, R., Karode, A., Lynch, A., Lynch, K., Munson, K., Ohlandt, C., Romano, D., Sanchez, R., Tripp, R., & Vesely, J. (2015). *Project AIR FORCE Modeling Capabilities for Support of Combat Operations in Denied Environments*. Santa Monica, CA: RAND Corporation.

- Wieberneit, N. (2008). Service network design for freight transportation: A review. *OR Spectrum*, 30, 77-112.
- Yin, Y., Madanat, S., & Lu, X. (2009). Robust improvement schemes for road networks under demand uncertainty. *European Journal of Operational Research*, vol. 198, no. 2, 470-479.
- Zheng, H., Son, Y., Chiu, Y., Head, L., Feng, Y., Xi, H., Kim, S., & Hickman, M. (2013). *A Primer for Agent-Based Simulation and Modeling in Transportation Applications*. McLean, VA: Federal Highway Administration.

Appendix A – AnyLogic Simulation Technical Details

The purpose of this appendix is to describe the inputs and relationships between variables in the AnyLogic simulation. It assumes a working knowledge of the AnyLogic software suite and utilizes standard terminology to describe the agents, relationships, and flow charts. Events and variables throughout this section are referred to by the names used on their specific flowcharts. The flowcharts discussed in this section are depicted in Figures 2-6. This section will first discuss the bases, then the factors within individual base flowcharts that dictate behavior, and will conclude with details on the C-17 agent statechart.

Base Agents & Placement

The three types of bases utilized in the simulation are created as stationary agents in Geographic Information Systems (GIS) space at the simulation start. The simplest agent is the MOB agent. This is always created at the airfield associated with Joint Base Pearl Harbor-Hickam. The LOB and FARP agents are created based on the criteria listed in the associated databases. These databases can be updated prior to simulation start and the number of agents for LOBs and FARPs is dictated by how many entries are made in the database tables. One agent is placed at each location. The LOB locations are shown in Table 2 and the FARP locations are shown in Table 3.

Table 2. Limited Operating Base Location List

Limited Operating Base Location List				
Latitude	Longitude	Name	Country	Location Feasibility
13.5882	144.9202	Anderson AFB, Guam	United States	High
9.4978	138.0866	Yap International Airport	Micronesia	High
7.3643	134.5320	Palau International Airport	Palau	High
5.3530	162.9563	Kosrae International Airport	Micronesia	Medium
6.9853	158.2091	Pohnpei International Airport	Micronesia	Medium
7.4622	151.8433	Chuuk International Airport	Micronesia	Medium
35.7332	139.3418	Yokota Air Force Base	Japan	Medium
9.3969	167.4709	Roi-Namur, Marshall Islands	Marshall Islands	Low
7.0690	171.2829	Marshall Islands International Airport	Marshall Islands	Low
19.8250	166.6367	Wake Island Airfield	United States	Low
-9.4275	160.0458	Honiara International Airport	Solomon Islands	Low
Notional Bases used for research				
Latitude	Longitude	Description		
23.1053	160.5775	Midpoint from MOB to FARP Cluster	Notional	N/A
19.9447	140.2572	Notional Base - Halfway from MOB to midpoint	Notional	N/A
23.5972	-178.5539	Notional Base - Halfway from midpoint to FARP Cluster	Notional	N/A

Table 3. FARP Location List

Latitude	Longitude	Name	Country	Military? Y/N
16.3970	120.6114	Camp John Hay	Philippines	Y
16.6197	120.2816	Wallace Air Station	Philippines	Y
14.9833	120.4833	Cesar Basa Air Base	Philippines	Y
15.1846	120.5569	Clarke Air Base/Int'l Airport	Philippines	N
14.7954	120.2827	NAS Subic Bay	Philippines	Y
6.9199	122.0616	Zamboanga Int'l Airport	Philippines	N
14.4881	120.8897	NAS Sangley Point	Philippines	Y
14.5123	121.0165	Manila Airport	Philippines	N
10.3107	123.9802	Mactan Cebu Airport	Philippines	N
11.6859	122.3809	Kalino Int'l Airport	Philippines	N
9.7457	118.7504	Puerto Princesa Int'l Airport	Philippines	N
7.1304	125.6455	Francisco Bangoy Int'l Airport	Philippines	N
11.2267	125.0261	Daniel Z. Romualdez Airport	Philippines	N
8.4078	124.6114	Lumbia Airfield	Philippines	N
26.2064	127.6465	Naha Airport	Japan	N
26.3557	127.7679	Kadena Air Base	Japan	Y
26.7226	127.7867	Iejima Airport	Japan	N
27.0437	128.4007	Yoron Airport	Japan	N
18.1810	121.7476	Cagayan North Domestic Airport	Philippines	N
17.6429	121.7353	Tuguegarao Airport	Philippines	N
16.3757	120.6131	Loakan Airport	Philippines	N
14.5123	121.0165	Ninoy Aquino Airport	Philippines	N
24.3970	124.2463	Painushima Ishigaki Airport	Japan	N

Order Messages

The order messages are used in the simulation to force aircraft movement due to resupply needs at the bases in the simulation. The simulation uses two types of order messages, which are created as agent class objects in the simulation. These are L_orders and A_orders. The messages function similarly and are routed through the pertinent base Process Modeling Flows via “msg” enter and exit blocks.

An L_order message is used to summon an aircraft from the MOB to a LOB. It is primarily generated by a LOB through the requestDelivery event. An L_order will also be generated if an A_order message is not matched with an aircraft within the time defined by the timeout1 variable. L_order messages consist of two parameters, the amount of supply requested and the location requesting resupply. When an L_order is matched to an aircraft at the MOB, the aircraft will proceed to the LOB in the L_order.

An A_order message is used to move aircraft between LOBs or to FARPs. An A_order message is generated at the FARP through the requestDelivery event. An A_order is generated at a LOB through the LOBDelivery event. An A_order message contains four parameters: amount of resupply requested, destination FARP, destination LOB, and priority. The priority parameter in an A_order message is increased when the message exits the match queue via timeout. This indicates that an aircraft is not available at the LOB within the timeout1 variable value and generates an L_order to summon an aircraft to the LOB to complete the FARP mission. An L_order is routed via the msg_enter block if it pertains to a FARP mission and is routed via the pri_msg_enter if the mission is a LOB resupply mission.

Events

Events occur within the simulation to stimulate action. Events occur at the main (root) level, FARP level, and LOB level. Events can occur at a variable rate, a set rate, or when certain conditions are met. These parameters are described with the applicable events.

Disruption events occur at the main level of the simulation and are represented by the `disruptLOB` event. The `disruptLOB` event occurs at a variable rate defined by the `disruptRate` parameter for the simulation. The `disruptLOB` event will occur at an average rate of this amount per day. When the event occurs, the action first counts the number of LOBs in the Open state. If this number is greater than zero, a LOB is randomly chosen from the LOBs in the Open state and the selected LOB is sent the message “Disrupt”. This moves the LOB from the Open state to the Disrupted state. The LOB will remain in this state until the time defined by the `disruptTime` parameter (located on the main level) is met.

FARP missions are created through the `requestDelivery` event on the FARP agent level. This event occurs daily at a rate defined by the `FARPdemand` parameter (located in main). When the event occurs, the action first checks if there are LOBs in the Open state. If a LOB exists in the Open state, a LOB will be randomly selected from the LOBs in the Open state. The event will send that LOB an `A_order` requesting a FARP mission, which requires between 4-8 supply units. If there are not any LOBs in the Open state, a LOB will be selected at random to receive the `A_order`.

The LOB agent level contains three categories of events, supply use/request events, timeout condition monitoring events, and the set event. The `UseSupplies` event occurs every hour and reduces the `supply_amount` by the amount defined by the `supplyUse` parameter (located on the main level). A `requestDelivery` event occurs at a set rate per day. The rate is defined by the equation “ $(\text{main.supplyUse} * 2.5) + (\text{main.FARPdemand} * \text{main.FARPs.size()})$ ”. When this event occurs, the action first checks the `supply_amount` value. If the `supply_amount` value is less than four days

supply, an L_order is generated requesting between 8 and 16 supply units to the LOB. The LOBDelivery event occurs in a similar fashion. The LOBDelivery rate is set at three times per day. First, the action checks the supply_amount value. If the value is less than two days' supply, an L_order is generated and delivered to the nearest LOB in the Open state for between 8 and 16 supply units.

The LOB level also contains the two events that can terminate the simulation early. These are categorized as timeout condition monitoring events. The low_supply event occurs every hour and checks the supply_amount value. If the value is less than or equal to zero, the simulation iteration is finished and the pertinent simulation data is recorded. The low_supply_FARP event also occurs once per hour and checks the maximum value of the distribution of the timeTotal block. This tracks the amount of time an A_order from a FARP delays before being matched to an aircraft. If this value exceeds 72 hours, the simulation is terminated and the pertinent simulation data is recorded.

The set event determines the values of the timeout and timeout1 variables. These variables are optimized to vary depending on the number of FARPs, FARPdemand, number of LOBs, and supplyUse variables. Early simulation testing revealed that imbalances between the number of FARP missions and LOB resupply missions could cause aircraft to be sub-optimally distributed. If the FARPdemand was significantly greater than the supplyUse, aircraft would not return to the MOB, leading to supply shortages in the system. Adjusting the timeout and timeout1 variables based on these values proved to improve the efficiency of the simulation across all values. The set event occurs at the simulation start and utilizes the supplyUse and FARPdemand variables to

set the timeout and timeout1 variables. The action input to set these variables is shown in Figure 24.

```
- Action
if ((8 - ((main.supplyUse - main.FARPdemand)*(main.supplyUse - main.FARPdemand))/((main.supplyUse + main.FARPdemand)/2)) > 2){
  timeout = (8 - ((main.supplyUse - main.FARPdemand)*(main.supplyUse - main.FARPdemand))/((main.supplyUse + main.FARPdemand)/2));
}
else
{
  timeout = 2;
}
if (24 - (2*((main.supplyUse - main.FARPdemand)*(main.supplyUse - main.FARPdemand))/((main.supplyUse + main.FARPdemand)/2)) > 16){
  timeout1 = 24 - (2*((main.supplyUse - main.FARPdemand)*(main.supplyUse - main.FARPdemand))/((main.supplyUse + main.FARPdemand)/2));
}
else
{
  timeout1 = 16;
}
```

Figure 24. Action Associated with Set Event

LOB Process Flow Block Details

This section provides additional details on the LOB Process Flow. The queue blocks represent parking space that can be utilized for aircraft, but cannot be used for uploads/downloads. The download, upload, and pri_upload blocks all operate similarly. They have a maximum queue size associated with them based on the Working_MOG resource pool size. The delay time associated with an upload or download is defined as a triangular time delay from 1, 1.5, to 2 hours. The hold block is activated when the LOB is moved to the Disrupted state. When the LOB is returned to the Open state, the hold is removed.

When a message arrives from another LOB (arrives in the pri_msg_enter block) due to a LOBDelivery event the priority variable is increased. If the priority variable is greater than zero, aircraft will be routed to the pri_upload block after download. After an aircraft is routed to this block, the priority variable is decreased. If the priority variable is equal to zero, aircraft will be routed to the parking block.

The pri_match block serves to match available aircraft with A_order messages. The match block serves to match aircraft with A_order messages and has additional

functions associated with aircraft or message timeout. If an aircraft is not matched with an A_order (indicating no required FARP missions) within the amount of time dictated by the timeout variable, it is routed back to the MOB. If a FARP A-order is not matched within the time defined by the timeout1 variable, it exits the match queue. Upon exit, an L_order is generated to summon an aircraft to the LOB. Additionally, the A_order message priority is increased by one and the order is returned to the message queue.

C-17 Agents

The C-17 agents are created at the beginning of the simulation and originate at the MOB. The agents move between bases at a speed of 400 knots. The number of agents is determined by the value of the aircraft parameter, located on the main level. The primary driver of aircraft agent behavior is the C-17 statechart. All agents enter the statechart at the GroundMOB state. When the agent is matched to an L_order at the MOB, the L_order triggers a transition to the FlyingToLOB state. The L_order parameters are stored as the variable L_order on the C-17 statechart. The limBases variable stores the destination LOB.

While in the FlyingToLOB state, the agent performs a continuous monitoring action. It first determines if the nearest LOB matches the destination LOB. When these values match, the agent checks the state of the LOB to determine if it is in the Disrupted state. If the LOB is Disrupted, the agent then selects a nearby base that is in the Open state and re-routes to that location. If no LOBs are in the Open state the aircraft will hold the current position for 30 minutes and increase the “hold_track” variable by one. This

variable represents the amount of time an aircraft can hold before handing at a suitable LOB. If this value reaches 4 (2 hours hold time), the simulation is terminated.

Upon transition to the GroundLOB state the aircraft agent enters the LOB flowchart. If the aircraft times out of the match queue, it receives a message directing a return to the MOB. The return to the MOB actions are depicted by the FlyingToMOB state and associated transitions. If instead the aircraft is matched with an A_order, it transitions out the left side of the GroundLOB state. If the aircraft has received an L_order directing the resupply of another LOB, it will follow the routing to the FlyingToLOB state. If instead, the message directs movement to a FARP, the aircraft will move to the FlyingToFARP state. Upon FARP arrival the aircraft will enter the FARPmission state and enter the FARP flowchart. Upon exit of the FARP flowchart, the aircraft will return to a LOB and re-enter the FlyingToLOB state.

Appendix B – Distance Comparison Tables

The distance calculations were completed using a straight-line distance between two geographic coordinates (latitude/longitude in decimal degrees) using the Vincenty ellipsoid formula to account for the curvature of the Earth. An excel add-in was used to complete the calculations quickly (**Latham, 2019**). The first distance calculated was the distance between the MOB and the possible LOBs (Table 4). Next, the distances between the LOBs and the FARP locations was calculated (Table 5). Finally, the total distance from the MOB to a FARP through a given LOB was calculated (Table 6).

Table 4. MOB to LOB Distance Comparison Table

	MOB to LOB Distances			
		Lat	Long	
Ref Point	Hickam	21.3393	-157.9584	Distance to Ref Point.
	Anderson AFB, Guam	13.5882	144.9202	6097.1
	Yap International Airport	9.4978	138.0866	6945.6
	Palau International Airport	7.3643	134.5320	7393.5
	Kosrae International Airport, Micronesia	5.3530	162.9563	4569.6
	Pohnpei International Airport, Micronesia	6.9853	158.2091	4970.4
	Chuuk International Airport, Micronesia	7.4622	151.8433	5600.5
	Yokota Air Force Base	35.7332	139.3418	6235.7
	Roi-Namur, Marshall Islands	9.3969	167.4709	3928.2
	Marshall Islands International Airport	7.0690	171.2829	3664.9
	Wake Island Airfield	19.8250	166.6367	3687.3
	Honiara International Airport	-9.4275	160.0458	5714.1

Table 5. LOB to FARP Distance Comparison Table

LOB/FARP Ref Distances	LOB Name Anderson		Yap Int'l	Palau Int'l	Kosrae Int'l	Pohnpei Int'l	Chuuk Int'l	Yokota	Roi-Namur	Marshall Islar	Wake Island	Honiara Int'l	
	Lat	13.5882	9.4978	7.3643	5.3530	6.9853	7.4622	35.7332	9.3969	7.0690	19.8250	-9.4275	
	Long	144.9202	138.0866	134.5320	162.9563	158.2091	151.8433	139.3418	167.4709	171.2829	166.6367	160.0458	
	Lat	Long											
Camp John Hay	16.3970	120.6114	2,631.3	2,042.5	1,814.6	4,776.6	4,221.1	3,537.2	2,835.3	5,133.1	5,604.4	4,871.6	5,198.4
Wallace Air Station	16.6197	120.2816	2,668.0	2,084.0	1,857.5	4,815.5	4,260.0	3,577.0	2,837.3	5,169.5	5,641.4	4,901.2	5,241.3
Cesar Basa Air Base	14.9833	120.4833	2,639.9	2,008.0	1,749.4	4,765.3	4,210.6	3,520.0	2,969.1	5,141.6	5,607.9	4,918.8	5,132.3
Clarke Air Base/Int'l Airport	15.1846	120.5569	2,632.2	2,006.5	1,752.8	4,760.8	4,205.9	3,516.2	2,946.4	5,134.2	5,601.2	4,906.0	5,136.4
NAS Subic Bay	14.7954	120.2827	2,661.5	2,023.4	1,759.3	4,783.7	4,229.2	3,537.6	2,998.5	5,162.7	5,628.3	4,944.6	5,141.1
Zamboanga Int'l Airport	6.9199	122.0616	2,608.6	1,788.3	1,378.3	4,528.5	3,993.5	3,289.3	3,645.8	5,008.4	5,436.1	5,016.9	4,584.4
NAS Sangley Point	14.4881	120.8897	2,596.4	1,951.6	1,685.6	4,714.2	4,159.9	3,467.4	2,988.5	5,096.8	5,561.3	4,888.9	5,067.4
Manila Airport	14.5123	121.0165	2,582.7	1,939.0	1,674.6	4,701.1	4,146.7	3,454.4	2,978.5	5,083.2	5,547.8	4,875.0	5,056.8
Mactan Cebu Airport	10.3107	123.9802	2,308.6	1,549.5	1,205.5	4,330.4	3,783.3	3,079.8	3,215.9	4,767.9	5,213.6	4,691.9	4,552.2
Kalino Int'l Airport	11.6859	122.3809	2,456.8	1,735.4	1,416.8	4,517.4	3,967.2	3,266.1	3,164.3	4,936.8	5,389.5	4,813.4	4,777.5
Puerto Princesa Int'l Airport	9.7457	118.7504	2,883.3	2,122.3	1,757.0	4,899.3	4,354.5	3,650.0	3,554.2	5,343.9	5,787.7	5,256.4	5,042.8
Francisco Bangoy Int'l Airpo	7.1304	125.6455	2,227.0	1,395.1	981.7	4,132.6	3,597.0	2,892.7	3,462.1	4,612.2	5,039.5	4,639.8	4,231.9
Daniel Z. Romualdez Airport	11.2267	125.0261	2,178.3	1,442.9	1,128.2	4,225.2	3,675.5	2,973.9	3,074.6	4,649.7	5,100.1	4,552.1	4,499.5
Lumbia Airfield	8.4078	124.6114	2,291.1	1,486.7	1,100.0	4,249.7	3,708.9	3,003.8	3,376.6	4,712.4	5,147.7	4,695.6	4,395.7
Naha Airport	26.2064	127.6465	2,280.8	2,152.5	2,209.4	4,405.5	3,874.7	3,297.0	1,535.2	4,588.0	5,080.4	4,043.7	5,275.0
Kadena Air Base	26.3557	127.7679	2,280.2	2,159.9	2,220.7	4,401.7	3,871.8	3,296.5	1,514.9	4,581.1	5,073.5	4,032.1	5,277.8
Iejima Airport	26.7226	127.7867	2,302.2	2,193.5	2,258.3	4,417.7	3,889.5	3,318.4	1,484.5	4,591.2	5,083.7	4,031.8	5,304.9
Yoron Airport	27.0437	128.4007	2,274.6	2,193.1	2,272.5	4,379.0	3,853.5	3,290.3	1,416.3	4,543.7	5,036.3	3,972.7	5,286.9
Cagayan North Domestic Ai	18.1810	121.7476	2,531.1	2,008.7	1,830.9	4,696.2	4,141.0	3,468.8	2,605.2	5,025.3	5,502.4	4,716.1	5,199.3
Tuguegarao Airport	17.6429	121.7353	2,524.6	1,984.1	1,794.8	4,685.0	4,129.6	3,454.0	2,653.0	5,021.9	5,497.4	4,727.8	5,168.3
Loakan Airport	16.3757	120.6131	2,631.0	2,041.5	1,813.2	4,776.0	4,220.5	3,536.6	2,837.0	5,132.9	5,604.1	4,871.9	5,197.1
Ninoy Aquino Airport	14.5123	121.0165	2,582.7	1,939.0	1,674.6	4,701.1	4,146.7	3,454.4	2,978.5	5,083.2	5,547.8	4,875.0	5,056.8
Painushima Ishigaki Airport	24.3970	124.2463	2,479.1	2,208.1	2,180.6	4,642.5	4,100.1	3,485.8	1,918.6	4,870.2	5,360.6	4,386.6	5,396.8

Table 6. Total Distance Comparison (MOB to FARP via LOB)

Round Trip Distances	Anderson	Yap Int'l	Palau Int'l	Kosrae Int'l	Pohnpei Int'l	Chuuk Int'l	Yokota	Roi-Namur	Marshall Islands	Wake Island	Honiara Int'l
Camp John Hay	8728.3887	8,988.1	9,208.2	9,346.2	9,191.5	9,137.8	9,070.9	9,061.4	9,269.3	8,559.0	10,912.5
Wallace Air Station	8765.1025	9,029.6	9,251.1	9,385.1	9,230.4	9,177.5	9,073.0	9,097.7	9,306.3	8,588.5	10,955.4
Cesar Basa Air Base	8737.0315	8,953.7	9,143.0	9,334.9	9,181.0	9,120.5	9,204.7	9,069.8	9,272.7	8,606.1	10,846.4
Clarke Air Base/Int'l	8729.3050	8,952.2	9,146.3	9,330.4	9,176.3	9,116.7	9,182.1	9,062.4	9,266.1	8,593.4	10,850.4
NAS Subic Bay	8758.6164	8,969.1	9,152.9	9,353.3	9,199.6	9,138.2	9,234.2	9,091.0	9,293.2	8,631.9	10,855.1
Zamboanga Int'l Airport	8705.7050	8,734.0	8,771.9	9,098.1	8,963.9	8,889.8	9,881.5	8,936.6	9,101.0	8,704.2	10,298.5
NAS Sangley Point	8693.5315	8,897.2	9,079.2	9,283.8	9,130.3	9,068.0	9,224.2	9,025.0	9,226.1	8,576.3	10,781.5
Manila Airport	8679.8291	8,884.6	9,068.2	9,270.6	9,117.1	9,054.9	9,214.2	9,011.4	9,212.6	8,562.4	10,770.8
Mactan Cebu Airport	8405.7000	8,495.2	8,599.0	8,900.0	8,753.7	8,680.3	9,451.6	8,696.1	8,878.5	8,379.2	10,266.3
Kalino Int'l Airport	8553.9182	8,681.0	8,810.3	9,087.0	8,937.6	8,866.7	9,400.0	8,865.1	9,054.3	8,500.8	10,491.6
Puerto Princesa Int'l	8980.3865	9,067.9	9,150.5	9,468.9	9,324.8	9,250.5	9,789.9	9,272.1	9,452.6	8,943.7	10,756.8
Francisco Bangoy Int'l	8324.1244	8,340.7	8,375.3	8,702.2	8,567.3	8,493.2	9,697.7	8,540.4	8,704.3	8,327.2	9,946.0
Daniel Z. Romualdez Airport	8275.3616	8,388.5	8,521.7	8,794.8	8,645.9	8,574.4	9,310.3	8,577.9	8,764.9	8,239.4	10,213.6
Lumbia Airfield	8388.1753	8,432.3	8,493.5	8,819.3	8,679.3	8,604.4	9,612.3	8,640.6	8,812.5	8,382.9	10,109.8
Naha Airport	8377.8641	9,098.1	9,602.9	8,975.1	8,845.1	8,897.5	7,770.9	8,516.3	8,745.2	7,731.0	10,989.1
Kadena Air Base	8377.3146	9,105.5	9,614.2	8,971.3	8,842.2	8,897.0	7,750.6	8,509.4	8,738.4	7,719.4	10,991.9
Iejima Airport	8399.3328	9,139.1	9,651.8	8,987.3	8,859.9	8,919.0	7,720.2	8,519.4	8,748.5	7,719.2	11,019.0
Yoron Airport	8371.7074	9,138.8	9,666.0	8,948.6	8,823.9	8,890.8	7,652.0	8,471.9	8,701.2	7,660.0	11,001.0
Cagayan North Domestic Airport	8628.2298	8,954.3	9,224.4	9,265.8	9,111.4	9,069.3	8,840.9	8,953.5	9,167.3	8,403.5	10,913.4
Tuguegarao Airport	8621.6816	8,929.7	9,188.4	9,254.6	9,100.0	9,054.5	8,888.7	8,950.1	9,162.3	8,415.1	10,882.4
Loakan Airport	8728.0651	8,987.1	9,206.8	9,345.6	9,190.9	9,137.1	9,072.7	9,061.1	9,268.9	8,559.3	10,911.2
Ninoy Aquino Airport	8679.8291	8,884.6	9,068.2	9,270.6	9,117.1	9,054.9	9,214.2	9,011.4	9,212.6	8,562.4	10,770.8
Painushima Ishigaki Airport	8576.1893	9,153.7	9,574.1	9,212.1	9,070.5	9,086.4	8,154.2	8,798.4	9,025.4	8,074.0	11,110.8

Appendix C – Commonly Used Acronyms

CONOP – Concept of Operations

FARP – Forward

LOB – Limited Operations Base

MAF – Mobility Air Forces

MHE – Materiel Handling Equipment

MOB – Main Operating Base

MOG – Maximum on Ground

NDS – National Defense Strategy

TRANSCOM – United States Transportation Command

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Global War on Terrorism Expeditionary Medal (1 OLC)

Global War on Terrorism Service Medal

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14. ABSTRACT The increased likelihood of conflict with a near-peer adversary has increased the likelihood of historically safe airbases coming under attack. One concept proposed to minimize the effects of this challenge is a distributed basing network. However, the impacts of this paradigm shift on the air logistics fleet have not been analyzed. This study developed an agent-based simulation to replicate permutations of a distributed airbase network. The requirements of the bases dictated the behavior of the aircraft agents in the simulation and allowed for the analysis of simulation outcomes. It also allowed for the replication of differently sized basing networks to assess the relationship between the size and needs of the basing network and the resupply requirements. The simulation was used to conduct numerous iterations of different distributed basing networks to assess the number of aircraft required to supply the bases. Trends in the data indicate relationships between distance, demand, and throughput capacity on the aircraft requirements. The simulation was also used to assess the effects of attacks on the transshipment nodes. These effects were studied and trends were identified to improve the understanding of how to build a more resilient logistics network. The data from the simulation indicated significant relationships and trends that can inform strategic planners of optimal ways to implement a base supply network. This analysis led to multiple recommended courses of action. Finally, limitations of the simulation were noted and areas of future research were identified that were deemed critical to furthering the understanding of developing a more resilient basing paradigm.					
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