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THESIS

OPTIMIZATION OF NAS LEMOORE SCHEDULING TO SUPPORT A GROWING AIRCRAFT POPULATION

by

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March 2017

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The current manual process for aircraft flight scheduling at Naval Air Station (NAS) Lemoore accommodates the independent needs of 16 fighter resident squadrons as well as constraints imposed by limited military operating area (MOA) availability. Given the complexity of this scheduling problem, attempting to additionally avoid periods of high activity, which lead to congestion, would challenge the manual process. Congestion leads to long wait times for flight-line services. Refueling operations are particularly costly when operational time is lost and resources are backlogged.

Avoiding inefficient periods of high demand for refueling operations is complicated by the two types of refueling available: hot refueling when the aircraft's engine is running or cold refueling when the aircraft is shut down. Although cold refueling is more fuel efficient, it is also more time consuming. Scheduling aircraft to avoid inefficient periods of high demand and achieving a balance between the two refueling methods are keys to maximizing the effectiveness of NAS Lemoore operations, particularly as Lemoore's aircraft population will grow in the coming years.

This thesis creates an optimization model to determine the best daily flight schedules based on current NAS Lemoore squadrons, the squadrons' flying and training requirements, the refueling infrastructure, and MOA availability. It also exercises the model to study the impact of the growing aircraft population estimated for 2017 and 2018.

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OPTIMIZATION OF NAS LEMOORE SCHEDULING TO SUPPORT A GROWING AIRCRAFT POPULATION

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ABSTRACT

The current manual process for aircraft flight scheduling at Naval Air Station (NAS) Lemoore accommodates the independent needs of 16 fighter resident squadrons as well as constraints imposed by limited military operating area (MOA) availability. Given the complexity of this scheduling problem, attempting to additionally avoid periods of high activity, which lead to congestion, would challenge the manual process. Congestion leads to long wait times for flight-line services. Refueling operations are particularly costly when operational time is lost and resources are backlogged.

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LIST OF ACRONYMS AND ABBREVIATIONS

C-40	aircraft used to transport passengers and cargo
CSFWP	Commander Strike Fighter Wing Pacific
CSV	comma separated values file
F/A-18 E/F	carrier-based multirole fighter aircraft
F-35	stealth multirole fighter aircraft
FCLP	field carrier landing practice
FLC	Fleet Logistics Center
GAMS	General Algebraic Modeling System
GPM	gallons per minute
JSF	Joint Strike Fighter
KNLC	ICAO airport code for Naval Air Station Lemoore
MOA	military operating area
MSISCHE	Multiple Squadron Input Schedule Enhancer
NAS	naval air station
NAVSUP	Naval Supply Systems Command
TRAINO	training officer
VBA	Visual Basic for Applications
VFA-XX	Strike Fighter Squadron XX (e.g., Strike Fighter 122)

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EXECUTIVE SUMMARY

Minimizing aircraft wait time during land-based refueling has both operational and resource management benefits. In-land aircraft refueling can be done by hot refueling, in which aircrafts' engines continue running during refueling, or by cold refueling, in which aircraft are shut down during refueling. Although cold refueling is more fuel efficient, it is also more time consuming; hot refueling can be completed faster than cold refueling and is used when aircraft need to immediately fly another mission, but it is more expensive and fuel inefficient due to the fuel burned while the aircraft's engines are running. Scheduling aircraft to avoid inefficient periods of high demand and achieving a balance between these two refueling methods are keys to maximizing the effectiveness of Naval Air Station (NAS) Lemoore operations.

NAS Lemoore's refueling demand is generated by its 16 home-based fighter squadrons and the sporadic arrival of transient aircraft, most commonly C-40 cargo aircraft. Refueling is provided by Naval Supply Systems Command (NAVSUP) Fleet Logistics Center (FLC) San Diego. NAS Lemoore has limited refueling resources: hot pits for conducting hot refueling, personnel for conducting both types of refueling, and fuel trucks for conducting cold refueling and as a means of transportation for refueling personnel to conduct hot refueling. The assignment of these resources is done on a first-come, first-served basis, creating a backlog during some peak hours while leaving refueling resources underused at other times.

To exacerbate the problem, the aircraft population at NAS Lemoore will grow in the coming years, especially 2017 and 2018. This growth will be due to the introduction of the Joint Strike Fighters (JSF) F-35 and relocation of one or more F/A-18 E/F squadrons. Given the current bottleneck experienced by aircraft waiting to be refueled, the additional future demand will likely exceed NAS Lemoore's refueling resources during peak demand times. Thus, it is prudent to consider optimizing the flying and refueling schedules now in order to operate the refueling system more efficiently and consequently improve the available flying time of the current and future aircraft.

At NAS Lemoore, the training officers of its home-based squadrons meet every Tuesday with Commander Strike Fighter Wing Pacific (CSFWP) staff to request and allocate Lemoore's military operating area (MOA) and field carrier landing practice (FCLP) hours for the following week. Additionally, each squadron, based on its training requirements, requests hours from MOAs and ranges from other bases and creates its own flight schedule independently from the other squadrons. Having the ranges pre-assigned a week prior to the flying week guarantees that squadrons will not fly to a range at a specific time if another squadron is planning to go to the same range at the same time. However, there are joint missions in which more than one event, from one or more squadrons, will fly to the same range at the same time. Because the squadrons do not communicate their schedules among themselves, and because the times when aircraft take off and land are not taken into account as a whole, there are times when the number of aircraft landing exceeds the capacity of the refueling system. This results in delays in aircraft turnaround times, which compound throughout the flight day leading to MOA scheduling conflicts and ultimately sortie cancellations.

After gathering data from CSFWP staff and NAS Lemoore Fuels Division, this thesis uses as inputs: the daily flight schedules of the 16 fighter squadrons, the estimated fuel to be consumed by each flight, the ranges assigned to squadrons, the number of refueling personnel available at various shifts during the day, the number of refueling trucks, the priority assigned to each squadron, the percentage of aircraft allowed to conduct hot refueling in a day, and the times to start and stop hot refueling determined by the refueling team. This thesis develops the optimization model Multiple Squadron Input Schedule Enhancer (MSISCHE), which is a linear mathematical optimization model based on series of penalties and rewards. MSISCHE takes as input the independent squadrons' planned schedules and finds the optimal set of minor adjustments to the take-off times that minimizes the refueling waiting time, and consequently maximizes the available flying time of aircraft refueling at NAS Lemoore. A critical characteristic of MSISCHE is that it seeks to make only small adjustments to the squadrons' requested schedule, thus preserving squadron authority and accountability, and identifies adjustments with the greatest positive impact on operational efficiency. To show the benefit of using the optimization model, we assess the aircraft refueling wait time based on the in-land refueling in both optimized and legacy operating protocols.

Since a new squadron is scheduled to arrive at NAS Lemoore between 2017 and 2018, this thesis evaluates the impact of modifying and growing the aircraft population. To include sensitivity analysis on some uncertain parameters, our study evaluates the impact of modifying the availability of fuel trucks and refueling personnel on the overall results.

The only way to control the number of aircraft refueling demands at specific times is by creating a merged flight schedule for NAS Lemoore that includes all 16 squadrons. Because of the numerous combinations, arranging the flights of 16 squadrons is quite difficult to accomplish by hand. An optimized refueling schedule can be obtained by utilizing the optimization model MSISCHE implemented in the General Algebraic Modeling System (GAMS). Using the squadrons' daily flight schedules a day before the actual flight allows limited opportunities to adjust schedules based on range availability. Future applications to enhance this model could use flight schedules a week prior the flying date, which will provide more flexibility on range changes.

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I. INTRODUCTION

> We are operating in challenging fiscal and operational times, and we must take appropriate action now to ensure the current and future vitality of Naval Aviation. To successfully achieve our missions today and in the future, all Naval Aviation stakeholders must be in sync and focused on the common goals of advancing readiness while reducing costs.
>
> —VADM D. Buss
> Commander, Naval Air Forces
> April 30, 2013

> Our number one priority is recovering and generating readiness so we can continue to send forces forward, as well as recovering readiness after 15 years of combat and the effects of sequestration. … Our ability to give squadrons the numbers of airplanes they need in maintenance phase has been very challenging, based on getting the airplanes and the parts … That's led to some limited flight hours for junior officers. We've taken that risk so those squadrons going through work-ups and deployments are getting resourced with what they need.
>
> —VADM M. Shoemaker
> Commander, Naval Air Forces
> September 13, 2016

> We all must be able to answer the question: Do you know what you do for the warfighter? … We must be ready so they are ready.
>
> —RADM J. A. Yuen,
> Commander, Naval Supply Systems Command and Chief of Supply Corps
> October 3, 2013

Maximizing aviation readiness is a continuous concern and priority to the Naval Air Forces. Even though any logistics team should make its best effort to meet the customer's demand, maximizing readiness goes beyond providing assets to meet any demand, which could be accomplished by adding resources whenever they appear to be insufficient. In order to have a balanced system, in which both outcomes and costs are important, logisticians must ensure that maximizing readiness also involves minimizing operational and resource costs.

A. BACKGROUND

There are two methods to conduct land-based aircraft refueling: hot and cold. In hot refueling, aircraft's engines are still operating, which means these aircraft must be equipped with a closed-circuit refueling receiver and single-point pressure refueling receiver that incorporate an automatic fuel shutoff capability. In cold refueling, the aircraft must shut down its engines, turn off all switches, and conduct a turnaround inspection prior to the refueling. The Naval Air Systems Command (NAVAIR) aircraft refueling manual 00-80T-109 provides definitions and guidelines for hot and cold refueling (NAVAIR, 2002). Although cold refueling is more fuel efficient, it is also more time consuming; hot refueling provides a much quicker turnaround. It would be easy to assume that the preferred method is hot refueling because it is faster than cold refueling; however, because fuel is consumed while refueling or waiting to refuel, hot refueling is costly. A squadron requests and schedules an aircraft to receive hot refueling if the aircraft needs to immediately fly another mission. Thus, achieving a balance between these two refueling methods and avoiding unmanageable peak demands are keys to maximizing the effectiveness of a refueling facility.

Naval Air Station (NAS) Lemoore is the home base of 16 fighter squadrons. A number of squadrons are deployed away from NAS Lemoore at any given time. Each of the remaining at-home squadron generates a flight schedule with its respective events a day prior to the actual flying date. Each event includes, among other information, the takeoff and landing times, the number of aircraft, the range where the aircraft will go, and the estimated fuel that will be burned in that event. The events of all squadrons are independently scheduled with the exception of joint missions in which multiple events from one or more squadrons will fly to the same range at the same time.

Because the squadrons do not communicate their schedules among themselves, and because the times when aircraft take off and land are not taken into account as a whole, there are times when the number of aircraft landing exceeds the capacity of the refueling system. The large number of aircraft coinciding in their landing time, in addition to the first-come, first-served distribution of the refueling resources, creates a backlog during some peak hours while leaving refueling resources underused in other times.

Additionally, NAS Lemoore's aircraft population will grow in the coming years, particularly in 2017 and 2018. This growth will be due to the introduction of the Joint Strike Fighters (JSF) F-35 and relocation of one or more F/A-18 E/F squadrons. Given the current bottleneck experienced by the aircraft waiting to be refueled during peak operational periods, the additional future demand will likely increase wait times for refueling if a new approach to scheduling is not developed. Optimizing the flying and refueling schedules in order to operate the refueling system more efficiently will improve the available flying time of the aircraft.

B. CURRENT FLIGHT SCHEDULING PROCESS AT NAS LEMOORE

Every Tuesday, the training officer (TRAINO) of each of NAS Lemoore's home-based fighter squadrons meets with Command Strike Fighter Wing Pacific (CSFWP) staff to request and allocate Lemoore's military operating area (MOA) and field carrier landing practice (FCLP) hours for the following week. Additionally, each squadron's TRAINO requests hours at MOAs and ranges from other bases from the respective base MOA/range coordinators; this occurs a week prior to flight. Figure 1 shows a small example of a report indicating when a particular MOA/range is assigned to squadrons during one week. The numbers in the cells represent the squadrons assigned each day and time, indicated by column and row respectively. Actual reports are more complex than this example, as each location usually includes many MOA/ranges, and it also covers more hours during the day.

	M		T		W		TH		F	
1000/1015			22	22					86	86
1030/1045		122	122	122	22	22	122	122		
1100/1115	122	122	122	94	22	22			86	86
1130/1145	94/22	94/22	94	94			122	122		
1200/1215	94/22	122	122	122			86	86	86	86
1230/1245	122	122	122		122	122	122	122		
1300/1315	94	94	94	94			86	86		
1330/1345	86	86	94				122	122		

Figure 1. Example of MOA/Range Assignments

The following week, each day, each TRAINO utilizes the MOAs assigned to his or her squadron along with the squadron's training requirements, and, without knowing the other squadrons' flight plans, creates his or her squadron's flight schedule. Figure 2 illustrates the process each squadron's TRAINO follows in order to create a daily flight schedule. Although these squadrons are geographically located at the same base, NAS Lemoore, they do not communicate their flight schedules among themselves; hence, the daily flight plan generated by each squadron is independently scheduled from the other squadrons. The only exception to this lack of communication occurs when planning a joint mission.

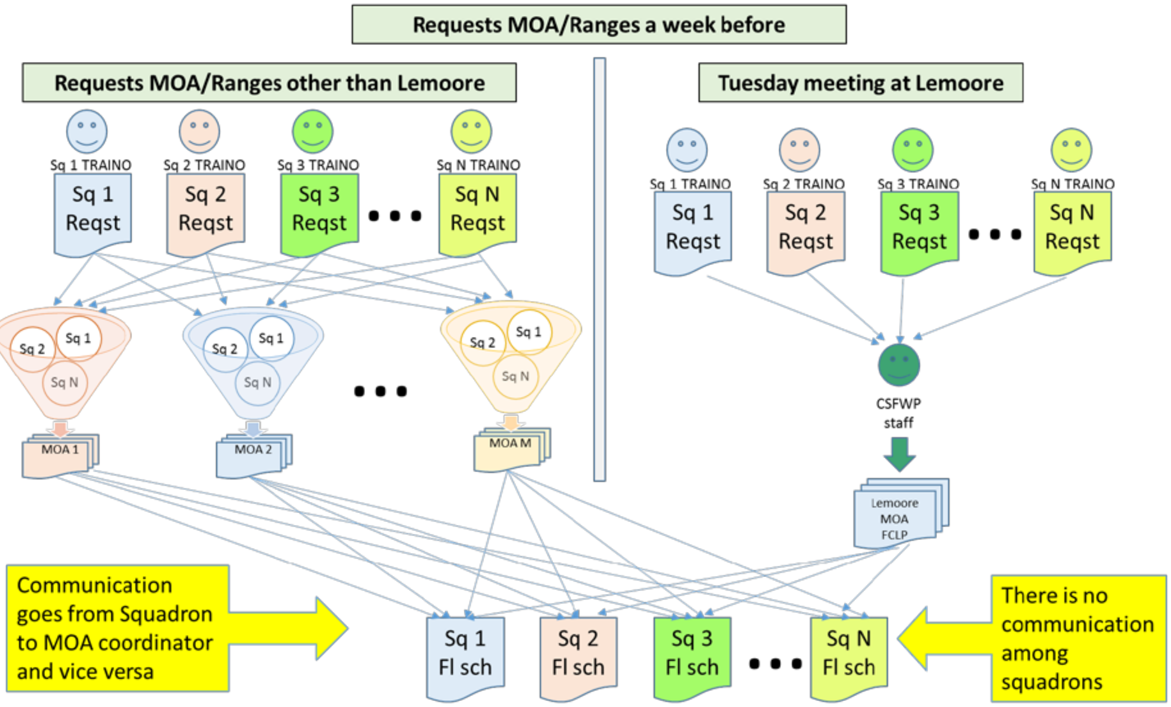

Figure 2. Squadrons' Flight Scheduling Process

C. CURRENT REFUELING PROCESS AT NAS LEMOORE

The Naval Supply Systems Command (NAVSUP) Fleet Logistics Center (FLC) San Diego provides aircraft refueling services at NAS Lemoore. The current refueling demand at NAS Lemoore is generated by its 16 home-based fighter squadrons and the sporadic arrival of a C-40 or other logistics aircraft. NAS Lemoore has limited refueling resources, including fuel skids or hot pits for conducting hot refueling, personnel for conducting both types of refueling, and fuel trucks for conducting cold refueling and as a means of transportation for refueling personnel to conduct hot refueling.

The fuel skids are available during specific hours, and each fuel skid is preassigned to specific squadrons due to its proximity to the squadrons' maintenance shop. Cold refueling is conducted at the ramp, which is also close to the squadrons' maintenance shop. The number of available personnel varies during the day. To avoid confusion with other personnel, this thesis uses the term "driver" as the designation for the refueling personnel and "maintainer" for personnel from the squadron's maintenance shop. The number of available fuel trucks may also vary due to routine or emergency maintenance requirements.

To conduct cold refueling, the following resources are needed: one driver, one fuel truck, and one maintainer. To perform hot refueling, the following resources are needed: one driver, one fuel truck, and two maintainers. Each fuel skid can refuel two aircraft simultaneously using its right and left hot pits. If the fuel skid is refueling two aircraft simultaneously, then the total needed resources are one driver, one fuel truck, and four maintainers.

Each squadron's maintenance shop submits a daily flight schedule to the refueling team indicating which aircraft require hot and cold refueling. The assignment of the refueling resources to each aircraft is generally done in a first-come, first-served manner. If an aircraft needs cold refueling, it will go to its pre-assigned ramp, shut down, and wait for a driver and a truck to be available. Only one driver with a truck goes to each ramp; another driver with a truck will assist cold refueling in the same ramp only if there are three or more aircraft waiting in queue in that ramp. If an aircraft needs hot refueling and the two sides of its pre-assigned fuel skid are already taken, the aircraft waits until the fuel skid becomes available. Hot refueling also occurs in a first-come, first-served manner.

NAS Lemoore Fuels Division records every refueling event. This information is used to track the percentage of hot refueling events and ensure that the percentage does not exceed the monthly allowed percentage.

D. PROBLEM

Refueling an aircraft involves the waiting time to receive fuel and the actual time consumed while receiving fuel. Although both cold and hot refueling should ideally be done without much waiting, hot refueling must be done expeditiously for two reasons: the cost of burning fuel and the need to ready the aircraft for its next scheduled event, which is what necessitated hot refueling in the first place. In general, it is beneficial to complete both types of refueling efficiently in order to increase flying time availability.

E. LITERATURE REVIEW

Because this thesis utilizes the concept of operational effectiveness, it is necessary to define this term. The Defense Acquisition University (DAU, 2015), in its website Glossary of Defense Acquisition Acronyms and Terms, describes operational effectiveness as "the overall ability of a system to accomplish a mission." Operational effectiveness can be improved by better resource utilization, which often requires changing operating policies.

A number of studies at the Naval Postgraduate School have sought ways to decrease the amount of time aircraft wait to refuel. Geiser (2012) recommends a set of solutions to reduce delays when refueling at NAS Oceana by modifying policy and materiel resources. By using simulation and data analysis, and focusing on improving communication to coordinate and dispatch refueling services, Geiser approaches the fuel demand problem at NAS Oceana. He emphasizes the communication flow between the squadrons and the fuel truck operators when the squadron's maintenance shop calls for refueling services. Moreover, Geiser's thesis explores techniques to help forecast the request for aircraft refueling and minimize the number of times fuel trucks need to refill when conducting aircraft refueling, which consequently decreases aircraft refueling time.

Gerber and Clark (2013) use simulation and data analysis to study refueling operations at NAS Lemoore. Specifically, they vary the aircraft arrival rate and determine the costs and benefits associated with the various policies, with aircraft fuel consumption and delay as their primary figures of merit. They first establish a baseline level of fuel consumed in the current practice; then consider the impact of future transitions to newer aircraft models in the coming years. Based on their analysis, Gerber and Clark recommend that planners "decrease variation in aircraft arrivals during peak periods by establishing a culture of squadron collaboration at the type-wing level through slot management" (p. 113).

Another study was conducted in winter 2015 by a group of 11 students, led by CDR Peter Ward, in the OA4611 Joint Logistics Models class at the Naval Postgraduate School (Ward, 2016). This team modeled and assessed the ability of refueling personnel, processes, and infrastructure at NAS Lemoore to meet future refueling demand around January 2017. They conclude that a range of policy changes, such as smoothing the refueling demand over the course of the operational day, would likely lead to the greatest reduction in refueling wait times.

Notably, prior research has focused on modeling and simulation of airfield operations. This thesis leverages the understanding of flight-line processes developed in prior work to apply the technique of mathematical optimization. This thesis takes a step towards the implementation of slot management as recommended by Gerber and Clark, although ours is a soft approach that values and maintains the autonomy of squadron inputs.

F. CONTRIBUTIONS AND OUTLINE

The goal of this thesis is to study the factors impacting the land-based refueling wait time at NAS Lemoore, and to determine whether the wait time can be reduced by modifying existing policies or through improved decision support. This thesis develops the Multiple Squadron Input Schedule Enhancer (MSISCHE), an optimization-based decision support tool designed to evaluate the squadrons' daily flight requests and the available refueling resources to create an optimal flying and refueling schedule. The current scheduling practice results in long wait times for refueling during periods of peak demand. These wait times are avoidable. MSISCHE makes small adjustments to scheduled takeoff times that are feasible given airspace scheduling constraints and deferential to squadron inputs. MSISCHE's adjustments smooth demand for limited resources such as refueling, making operations at NAS Lemoore more efficient.

Through optimization and sensitivity analysis, we identify critical elements that impair and constrain the efficiency of land-based aircraft refueling service at NAS Lemoore. The most significant outcome in our study is that, with the current squadrons and refueling infrastructure at NAS Lemoore, MSISCHE is able to find a combined optimal solution that minimizes the aircraft refueling wait time while making only small adjustments to the squadrons' flight schedules.

With the current aircraft refueling demand at NAS Lemoore, the refueling resources are at the edge of sustainability. In order to maintain a balanced system, the refueling demand cannot surpass the available refueling resources. Decreasing the refueling resources or increasing the number of squadrons will force the cancellation of some flying events.

We highly recommend the use of MSISCHE to improve the efficiency of the scheduling process at NAS Lemoore while minimizing changes to the squadrons' flight schedules and deriving the benefits of reduced refueling wait times.

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II. METHODOLOGY

This study was conducted by gathering data from CSFWP and the NAS Lemoore Fuel Division, reviewing previous studies, setting up constraints, limitations, and assumptions, developing the optimization model, creating an interface, and generating scenarios needed to test the model and perform sensitivity analysis.

A. OBJECTIVES

Minimizing the time aircraft spend waiting for refueling service is of paramount importance. However, when refueling demands are concentrated during specific times of the day, there is a natural tension between the customer for refueling who expect immediate service even during periods of peak demand, and the refueling service provider team for whom it would be inefficient to be resourced to support peak demand with idle capability at all other times. Providing additional resources to avoid refueling delays during even peak demand periods might be the best solution from the customer's perspective, but this is treating a symptom rather than addressing a root cause and does not address other effects of congestion on the flight-line or in the airspace. Also, resourcing to meet peak demand is just a temporary solution; eventually, the backlog will return either as the number of aircraft increases or the times of peak demand shift. A deeper analysis is needed to address the root cause of the problem, and consequently develop a robust solution.

The peak demand hours and resulting congestion occur because aircraft participating in one or more events, from one or more squadrons, coincide in their landing time and thus in the time at which they require refueling. This issue can be mitigated by coordination of the squadrons' flight schedules. Because of the complexity involved, reconciling the schedule requests from individual squadrons with an overall objective of avoiding peak demands would be tedious and time consuming to accomplish manually. In addition to the scheduling process, a further area of exploration is the policy of pre-assigning fuel skids to specific squadrons. This policy might be advantageous because the hot skids are close to the squadron's maintenance facility, but it is also a disadvantage because this assignment constrains the squadron's aircraft to wait for refueling if their assigned hot skid is occupied while other hot skids are available. Having aircraft from 16 squadrons creates a high demand, but with the proper coordination of the squadrons and the refueling team, landing and refueling of aircraft can be executed more efficiently than is currently observed. Reducing the aircraft's refueling waiting time increases the aircraft's available flying time.

Our study is based on data provided by CSFWP staff and NAS Lemoore Fuels Division. This thesis develops, in the General Algebraic Modeling System (GAMS) (GAMS, 2015), the optimization model Multiple Squadron Input Schedule Enhancer (MSISCHE), which is a discrete-time mixed integer linear mathematical optimization model based on series of penalties and rewards. MISISCHE uses as inputs the daily flight schedules developed by the squadrons present at NAS Lemoore, the estimated fuel to be consumed by each flight, the MOA ranges assigned to squadrons, the priority assigned to each squadron, the number of refueling personnel in the various shifts, the number of refueling trucks, the capacity and safety levels of the refueling trucks, the percentage of aircraft allowed to conduct hot refueling in a day, and the times to start and stop hot refueling determined by the refueling team.

A central precept of MSISCHE is to respect the daily flight schedules developed by the individual squadrons to the greatest extent possible. By making only small adjustments to the timing of events proposed by the squadrons, MSISCHE finds the optimal solution to the flight schedules at NAS Lemoore where optimal is defined as a balance between the minimization of refueling waiting time (and consequently maximization of the aircraft's flying time availability) and minimization of deviation from the squadron' proposed schedules. MSISCHE identifies and makes these small adjustments with the greatest positive impact on operational efficiency while preserving squadrons' authority and accountability.

To demonstrate the benefit of using the optimization model, the study assesses the operational availability of the aircraft based on the in-land refueling in both optimized and legacy operating protocols. In addition to the current situation, this thesis evaluates the impact of growing the aircraft population, and modifying some uncertain parameters such as the availability of the fuel trucks and the number of refueling personnel.

B. SCOPE, CONSTRAINTS, LIMITATIONS, AND MODEL ASSUMPTIONS

1. Scope

This thesis provides a model to optimize the current daily flight schedules generated by NAS Lemoore's fighter squadrons for the following day in order to provide an alternate and optimal combined schedule that minimizes aircraft refueling waiting time, and accordingly maximizes aircraft available flying time. NAS Lemoore's combined schedule is generated by utilizing all the data, in comma separated values (CSV) files, from the squadrons' daily flight schedules, and data regarding the available refueling resources. By using the optimization model MSISCHE, this thesis shows that it is possible to have a collective schedule that, with only small adjustments to the squadrons' requested schedules, guarantees the balance between minimizing schedule changes and minimizing aircraft's refueling wait time.

2. Constraints

- CSFWP can modify only the pre-assigned times of events going to Lemoore MOAs and FCLPs.
- Times of events going to MOAs and ranges other than NAS Lemoore are pre-assigned a week prior to the event and cannot be modified on short notice.

3. Limitations

- The model minimizes the refueling wait time by shifting events in small increments before or after the requested takeoff time given by the respective squadron. This self-imposed limitation is set in order to preserve the authority and accountability of individual squadrons.
- Events represent a group of one or more aircraft going to a specific range, and at a specific time, to complete a mission. Missions are represented by a code. The study was not able to gather information linking the mission code to a range.
- The model accounts only for the refueling services provided to NAS Lemoore's squadrons. If other aircraft are visiting NAS Lemoore and

require refueling, these requirements must be added to the model in order to take full advantage of the optimization.

- Besides refueling, the fuel truck operators have other duties on base; nonetheless, there is not enough data to represent these other duties, consequently they are not taken into consideration.

4. Assumptions

This thesis assumes the following in order to produce a mathematical model that optimizes NAS Lemoore's combined flight schedule. Many of these assumptions can be modified by changing their corresponding parameters in MSISCHE. To avoid repetition in most of the assumptions, and because MSISCHE runs utilizing the squadrons' flight schedules for a specific date, when an assumption says that a parameter remains constant it actually means that this parameter remains constant on that date.

- All events, including refueling of aircraft and trucks, are based on time periods of 15-minute increments.
- Drivers work following their schedule, and they are available for the entire shift.
- Fuel trucks have perfect reliability. The number of fuel trucks remains constant, unless one breaks down or needs to be refueled.
- The safety level percentage of the fuel trucks, which indicates when the truck needs to be refueled, remains constant.
- Available trucks are used if there are enough drivers.
- Trucks' fuel capacity remains constant.
- Fuel trucks are filled to their maximum capacity before starting the day.
- Hot refueling is allowed only during the hours set by NAS Lemoore Fuels Division.
- Cold refueling is available 24 hours per day.
- In a 15-minute period, an aircraft can be refueled up to 1,800 gallons.
- Aircraft requesting hot refuel could do so at any hot pit.
- All fuel skids are operational and available.

- CSFWP provides the priorities for each squadron, giving VFA-122 the highest priority and squadrons preparing to deploy the next highest priority.
- CSFWP provides the penalty incurred for each squadron for a shift in one 15-minute time interval to an event's requested takeoff time.
- CSFWP provides the Lemoore MOAs available hours for the day.
- Aircraft could fly to any of the MOA/ranges included in the NAS Lemoore Inflight Guide 2016 (CSFWP, 2016).
- Transit time to MOA/ranges is assumed as one time period (15 minutes) for most MOA/ranges, and zero time periods for Lemoore, Hunter, FCLP, R_2508, and Ferry.
- All squadrons' flight schedules used as inputs are valid for the following day, and they are provided using time periods of 15-minute increments.
- Some events do not land back at NAS Lemoore Airport (KNLC), and this situation is noted in the flight schedule.
- Events going to joint missions are annotated in the flight schedule.
- The estimated fuel burned in each event is annotated in the flight schedule.
- More than one not-joint event could go to certain missions at the same time (FDMO, Ferry, and missions going to range R_2508).
- Because events in the squadrons' flight schedules do not include aircraft's designation, aircraft in the model are not utilized in more than one event; however, aircraft that require hot refueling effectively model an aircraft that is going to perform multiple events.
- To include the possibility of more constraints, Lemoore MOA is not available all day; instead, it is available during the hours of 0930–1130, 1300–1500, and 1630–2400.
- Events scheduled for Lemoore MOA, FCLP, FDMO, R_2508, and Ferry can be modified on a short notice.
- The monthly percentage of refueling events allowed to conduct hot refueling applies equally to any day.
- There is no restriction on the number of aircraft that can take off at the same time.
- There is no restriction on the number of aircraft that can land at the same time.

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III. THE MSISCHE OPTIMIZATION MODEL

MSISCHE has three components: a Microsoft Excel interface (Microsoft, 2013), a discrete-time linear optimization model implemented in GAMS (GAMS, 2015), and a body of Visual Basic for Applications (VBA) code that links the two. The user interacts with MSISCHE via the Excel-based interface, while the VBA and GAMS code remain invisible to the user.

A. INTERFACE

Figure 3 through 5 present a few snapshots of the interface. Figure 3 shows the Dashboard, the first and main sheet of MSISCHE's interface. It contains some parameters that the user can modify, a usage guide, and a number of buttons that allow the user to utilize various functions.

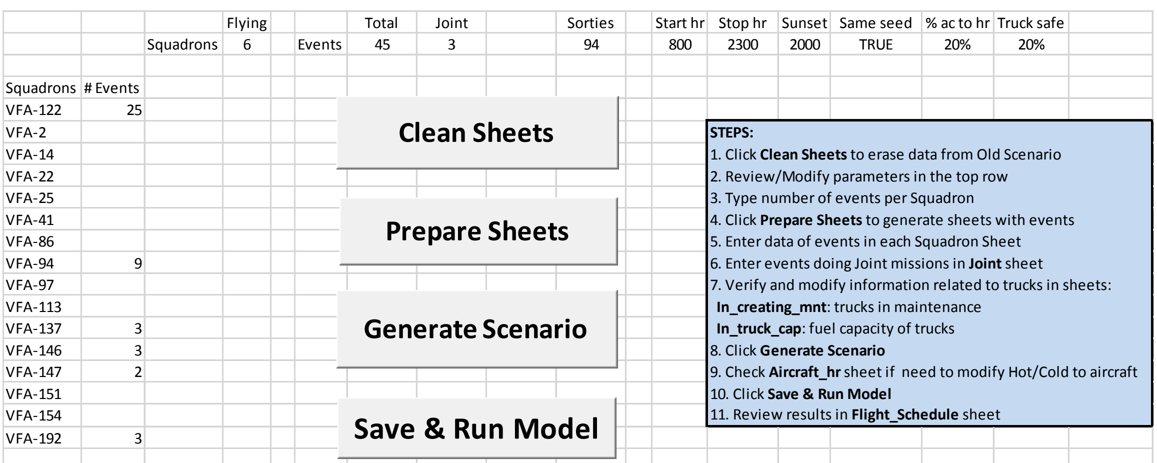

Figure 3. Snapshot of the Dashboard Worksheet, MSISCHE's Interface

Figure 4 shows how, by using the squadrons' worksheets, the user enters the data corresponding to the events of the daily flight schedules. The worksheet includes a few notes to guide the user on the proper formatting when entering the data.

	take-off	land	fuel	joint	KNLC	Range	Sorties	Hot/Cold
V122-e1	1000	1130	12	0	1	R_2508	1	1
V122-e2	1200	1330	17	0	1	R_2508	1	0
V122-e3	1200	1315	17	0	1	R_2508	2	0
V122-e4	1200	1315	17	0	1	Hunter_High	2	1
V122-e5	1215	1345	17	0	1	R_2508	1	0
V122-e6	1245	1415	17	0	1	R_2508	1	0
V122-e7	1315	1445	17	0	1	Superior_Valley	4	0
V122-e8	1315	1400	13	0	1	FCLP	4	0
V122-e9	1400	1515	17	0	1	R_2508	2	1
V122-e10	1400	1515	17	0	1	Hunter_High	2	0
V122-e11	1445	1530	13	0	1	FCLP	4	0
V122-e12	1445	1530	13	0	1	R_2508	1	0
V122-e13	1600	1715	17	0	1	Hunter_High	2	1

Notes:
Take-off: time in periods of 15 minutes
Land: time in periods of 15 minutes
Fuel: estimated in pounds
Joint: number of events going with event at the same mission
KNLC: 1 if event will finish landing at KNLC, 0 otherwise
Range: where the event is going
Sorties: number of aircraft of the event
Hot/Cold: 1 if required hot refueling, 0 if cold

Figure 4. Snapshot of a Squadron Input Worksheet, MSISCHE's Interface

After generating the scenario, saving it, and running the model, the interface presents the results through the Flight Schedule worksheet. Figure 5 illustrates part of the results.

Flight Schedule								
Squadron:	VFA-122		Desired	Time	Computed	Time	Start	
Event	Aircraft	Range	T-Off	Land	T-Off	Land	Refuel	Hot/Cold
V122-e1	V122-a1	R_2508	815	1000	815	1000	1000	Hot
V122-e1	V122-a2	R_2508	815	1000	815	1000	1000	Hot
V122-e2	V122-a3	Ferry	1515	1545	1515	1545	1545	Cold
V122-e3	V122-a4	Fallon_N2	930	1030	930	1030	1030	Hot
V122-e3	V122-a5	Fallon_N2	930	1030	930	1030	1030	Hot
V122-e4	V122-a6	R_2508	945	1045	945	1045	1045	Hot
V122-e5	V122-a8	R_2508	830	915	830	915	915	Hot
V122-e5	V122-a9	R_2508	830	915	830	915	915	Hot
V122-e6	V122-a12	Superior_Valley	1100	1200	1100	1200	1200	Hot
Squadron:	VFA-2		Desired	Time	Computed	Time	Start	
Event	Aircraft	Range	T-Off	Land	T-Off	Land	Refuel	Hot/Cold
V2-e1	V2-a1	Lemoore_A	1345	1430	1345	1430	1430	Hot
V2-e1	V2-a2	Lemoore_A	1345	1430	1345	1430	1430	Hot
V2-e2	V2-a4	R_2508	1830	1900	1830	1900	1900	Hot
V2-e2	V2-a6	R_2508	1830	1900	1830	1900	1900	Hot

Figure 5. Snapshot of Flight Schedule Worksheet Results, MSISCHE's Interface

The interface workbook has approximately 50 worksheets, but many of them contain intermediate steps and are hidden because they should not be modified by users.

B. MODEL FORMULATION

We now describe MSISCHE's mathematical formulation.

1. Indices and Sets [Approximate Cardinality]

$i, i' \in I$	Squadrons	[16]
$j, j' \in J$	Events	[~500]
$k, k' \in K$	Aircraft	[~550]
$r \in R$	Ranges/MOAs	[~114]
$t \in T = \{t1, .., t11\}$	Refueling Trucks	[11]
$q, q', q'' \in Q$	Time periods	[128]

$E \subseteq I \times J$	Mapping of pairs (*i*,*j*): squadron *i* requests event *j*
$A \subseteq J \times K$	Mapping of pairs (*j*,*k*): aircraft *k* performs event *j*
$ER \subseteq J \times R$	Mapping of pairs (*j*,*r*): event *j* requires range *r*
$EJ \subseteq J \times J$	Mapping of tuples (j, j') : events j and j' belong to a joint mission
$M \subseteq I \times R \times Q$	Mapping of triplets (*i*,*r*,*q*): squadron *i* can occupy range *r* at time *q*
$M' \subseteq I \times R \times Q$	Mapping of triplets (*i*,*r*,*q*): squadron *i* going to range *r* can take off at time *q*
$N \subseteq J \times K \times R \times Q \times Q$	Mapping of tuples (j, k, r, q, q') : aircraft *k* of event *j* can go to range *r* taking off at time *q* and refueling at time q'
$TRUCKN \subseteq J \times K \times T \times Q$	Mapping of tuples (j, k, t, q) : aircraft *k* of event *j* can be refueled by truck *t* at time *q*
$Q^H \subseteq Q$	Set of time periods when hot refueling is available
$Q^{NH} \subseteq Q$	Set of time periods when hot refueling is not available
$R^1 \subseteq R$	Set of ranges that may have more than 1 event at the same time
$J^1 \subseteq J$	Set of events that will land and refuel in Lemoore (KNLC)
$K^1 \subseteq K$	Set of aircraft assigned to do hot refuel

2. Parameters [Units]

to_j	Requested takeoff time of event *j* [time period]
la_j	Requested landing time of event *j* [time period]
ff_j	Estimated fuel consumed by event *j* [1000 lbs]
$joint_j$	Number of events going with event j to a joint mission

	[events]
tr_r	Number of time periods to reach range *r* [time periods]
pr_i	Priority assigned to squadron *i* [reward]
pc_i	Penalty for changing takeoff time of events of squadron *i* [penalty]
pw	Penalty for an aircraft waiting to refuel [penalty]
pt	Penalty per thousand gallon fuel shortage of truck below safety level [penalty/1000 gal]
$capt_t$	Fuel capacity of truck *t* [1000 gallons]
$safe$	Percentage of fuel capacity below which trucks incur a penalty [percentage]
np_q	Number of fuel personnel assigned to time period *q* [drivers]
nhp	Number of hot-fuel skids [hot fuel-skids]
ncp	Number of cold pits [cold pits]
$mnt_{t,q}$	1 if truck *t* is in maintenance in time period *q*, 0 otherwise [binary]
$ptog$	Factor to convert pounds of fuel to gallons [0.15 gal/lb]
$hrpercent$	Percentage of aircraft allowed to do hot refueling [percentage]

3. Derived Data [Units]

et_j — Estimated flying time of event *j* [time periods]

$$et_j = la_j - to_j \qquad \forall\ i, j : (i, j) \in E$$

$etfa_j$ — Estimated time to refuel aircraft of event *j* [time periods]

$$etfa_j = \left\lceil \frac{ptog * ff_j}{1.8} \right\rceil \qquad \forall\ i, j : (i, j) \in E$$

$pec_{j,q}$ — Penalty to an aircraft of event *j* for changing its takeoff time to time period *q* [penalty]

$$pec_{j,q} = 0.05 * pr_i * pc_i * \left| \frac{q - to_j}{96} \right| \qquad \forall\ i, j, q : (i, j) \in E$$

$pew^h_{j,q,q'}$ — Penalty to an aircraft of event *j* for waiting for hot refueling between landing time *q* and refueling time q' [penalty]

$$pew^h_{j,q,q'} = 0.75 * pr_i * pc_i * pw * \left(\frac{q' - (q + et_j)}{96} \right)$$
$$\forall\ j, k, r, q, q' : (j, k, r, q, q') \in N$$

$pew^c_{j,q,q'}$ — Penalty to an aircraft of event *j* for waiting for cold refueling between landing time *q* and refueling time q' [penalty]

$$pew^{c}_{j,q,q'} = 0.05 * pr_i * pc_i * pw * \left(\frac{q' - (q + et_j)}{96} \right)$$
$$\forall\, j,k,r,q,q' : (j,k,r,q,q') \in N$$

4. Variables [Units]

$Y_{j,r,q}$	1 if event *j* arrives at range *r* at time *q* [binary]
$X^{h}_{j,k,r,q,q'}$	1 if aircraft *k* of event *j* going to range *r* takes off at time *q* and starts hot refueling at time q' [binary]
$X^{c}_{j,k,r,q,q'}$	1 if aircraft *k* of event *j* going to range *r* takes off at time *q* and starts cold refueling at time q' [binary]
$W^{h}_{j,k,t,q}$	1 if aircraft *k* of event *j* uses truck *t* to start hot refueling at time *q* [binary]
$W^{c}_{j,k,t,q}$	1 if aircraft *k* of event *j* uses truck *t* to start cold refueling at time *q* [binary]
$REFUEL_{t,q}$	1 if truck *t* is getting fuel at at time *q* [binary]
$SHORT_{t,q}$	Amount by which truck *t*'s fuel is below safety level at time *q* [1000 gal]
$HOLD_{t,q}$	Fuel inventory of truck *t* at start time *q* [1000 gal]
$FT_{t,q}$	Fuel received by truck *t* at time *q* [1000 gal]
$FA_{j,k,t,q}$	Fuel received by aircraft *k* of event *j* from truck *t* at time *q* [1000 gal]

5. Formulation

$$\underset{\substack{Y, X^h, X^c, W^h, W^c, \\ REFUEL, SHORT, \\ HOLD, FT, FA}}{Max} \sum_{\substack{j,k,r,q,q' : \exists i: \\ (i,j) \in E, \\ k \in K^1, \\ (j,k,r,q,q') \in N, \\ q' \in Q^H}} \left(pr_i - pec_{j,q} - pew^{h}_{j,q,q'} \right) X^{h}_{j,k,r,q,q'}$$
$$+ \sum_{\substack{j,k,r,q,q' : \exists i: \\ (i,j) \in E, \\ k \notin K^1, \\ (j,k,r,q,q') \in N}} \left(pr_i - pec_{j,q} - pew^{c}_{j,q,q'} \right) X^{c}_{j,k,r,q,q'} - \sum_{t,q} pt * SHORT_{t,q}$$

s.t.

$$\sum_{\substack{r,q,q': \\ (j,k,r,q,q')\in N, \\ k\in K^1, \\ q'\in Q^H, \\ (j,r)\in ER}} X^{h}_{j,k,r,q,q'} + \sum_{\substack{r,q,q': \\ (j,k,r,q,q')\in N, \\ k\notin K^1, \\ (j,r)\in ER}} X^{c}_{j,k,r,q,q'} \le 1 \qquad \forall\, j,k : (j,k)\in A \qquad (1)$$

$$\sum_{\substack{j,k,r,q,q': \\ (j,k,r,q,q')\in N, \\ k\in K^1, \\ j\in J^1 \\ q'\in Q^H}} X^{h}_{j,k,r,q,q'} \le hrpercent * \left(\sum_{\substack{j,k,r,q,q': \\ (j,k,r,q,q')\in N, \\ k\in K^1, \\ j\in J^1 \\ q'\in Q^H}} X^{h}_{j,k,r,q,q'} + \sum_{\substack{j,k,r,q,q': \\ (j,k,r,q,q')\in N, \\ k\notin K^1, \\ j\notin J^1}} X^{c}_{j,k,r,q,q'} \right) \qquad (2)$$

$$\sum_{\substack{j,q':\exists i: \\ (i,j)\in E, \\ (i,r,q)\in M, \\ (i,r,q')\in M, \\ (q-et_j+tr_r+1\le q'\le q)}} \frac{Y_{j,r,q'}}{(1+joint_j)} \le 1 \qquad \forall\, q,r : r\notin R^1 \quad (3)$$

$$\sum_{\substack{q': \\ (j',k',r,q,q')\in N, \\ k'\in K^1, \\ q'\in Q^H}} X^{h}_{j',k',r,q,q'} + \sum_{\substack{q': \\ (j',k',r,q,q')\in N, \\ k'\notin K^1}} X^{c}_{j',k',r,q,q'} = \sum_{\substack{q': \\ (j,k,r,q,q')\in N, \\ k\in K^1, \\ q'\in Q^H}} X^{h}_{j,k,r,q,q'} + \sum_{\substack{q': \\ (j,k,r,q,q')\in N, \\ k\notin K^1}} X^{c}_{j,k,r,q,q'}$$

$$\begin{aligned} \forall\, j,k,r,q,j',k' : \exists i,i' : (j,j')\in EJ \text{ and } (i,j)\in E \text{ and } (i',j')\in E \text{ and} \\ (j\ne j') \text{ and } (\text{joint}(j)>0) \text{ and } (\text{joint}(j')>0) \text{ and} \\ (j,r)\in ER \text{ and } (j',r)\in ER \text{ and } (j,k)\in A \text{ and} \\ (j',k')\in A \text{ and } (i,r,q)\in M' \text{ and } (i',r,q)\in M' \end{aligned} \qquad (4)$$

$$\sum_{\substack{q': \\ (j,k,r,q,q')\in N, \\ k\in K^1, \\ q'\in Q^H}} X^{h}_{j,k,r,q,q'} + \sum_{\substack{q': \\ (j,k,r,q,q')\in N, \\ k\notin K^1}} X^{c}_{j,k,r,q,q'} = Y_{j,r,q+tr(r)}$$

$$\forall\, j,k,r,q : \exists i : (i,j)\in E \text{ and } (j,k)\in A \text{ and } (j,r)\in ER \text{ and } (i,r,q)\in M' \qquad (5)$$

$$\sum_{\substack{t: \\ (j,k.t.q')\in TRUCKN}} W^{h}_{j,k,t,q'} = \sum_{\substack{q: \\ (j,k,r,q,q')\in N}} X^{h}_{j,k,r,q,q'}$$

$$\forall\, j,k,r,q' : j\in J^1 \text{ and } (j,k)\in A \text{ and } k\in K^1 \text{ and } (j,r)\in ER \text{ and } (q'\in Q^H) \quad (6)$$

$$\sum_{\substack{t:\\ (j,k.t.q')\in TRUCKN}} W^{c}_{j,k,t,q'} = \sum_{\substack{q:\\ (j,k,r,q,q')\in \mathrm{N}}} X^{c}_{j,k,r,q,q'}$$

$$\forall\, j,k,r,q' : j \in J^1 \text{ and } (j,k) \in A \text{ and } k \notin K^1 \text{ and } (j,r) \in ER \qquad (7)$$

$$REFUEL_{t,q} + \frac{1}{2} \sum_{\substack{j,k,q':\\ (j,k,t,q')\in TRUCKN,\\ q'\in QH,\\ k\in K^1,\\ q-etfa_j+1\le q'\le q}} W^{h}_{j,k,t,q'} + \sum_{\substack{j,k,q':\\ (j,k,t,q')\in TRUCKN,\\ k\notin K^1,\\ q-etfa_j+1\le q'\le q}} W^{c}_{j,k,t,q'} \le 1 - mnt_{t,q} \qquad \forall\, t,q \quad (8)$$

$$\sum_{\substack{j,k,t,q':\\ (j,k,t,q')\in TRUCKN,\\ k\notin K^1,\\ q-etfa_j+1\le q'\le q}} W^{c}_{j,k,t,q'} \le ncp \qquad \forall\, q \quad (9)$$

$$\frac{1}{2} \sum_{\substack{j,k,t,q':\\ (j,k,t,q')\in TRUCKN,\\ q'\in QH,\\ k\in K^1,\\ q-etfa_j+1\le q'\le q}} W^{h}_{j,k,t,q'} \le nhp \qquad \forall\, q \quad (10)$$

$$\sum_{t} \left(REFUEL_{t,q} + \frac{1}{2} \sum_{\substack{j,k,q':\\ (j,k,t,q')\in TRUCKN,\\ q'\in QH,\\ k\in K^1,\\ q-etfa_j+1\le q'\le q}} W^{h}_{j,k,t,q'} + \sum_{\substack{j,k,q':\\ (j,k,t,q')\in TRUCKN,\\ k\notin K^1,\\ q-etfa_j+1\le q'\le q}} W^{c}_{j,k,t,q'} \right) \le np_q \qquad \forall\, q \quad (11)$$

$$HOLD_{t,q1} = capt_t \qquad \forall\, t \quad (12)$$

$$HOLD_{t,q} \le capt_t \qquad \forall\, t,q \quad (13)$$

$$FT_{t,q} \le capt_t * (REFUEL_{t,q} + mnt_{t,q}) \qquad \forall\, t,q \quad (14)$$

$$FA_{j,k,t,q} = \frac{ptog * ff_j}{etfa_j} * \sum_{\substack{q':\\ (j,k,t,q')\in TRUCKN,\\ q-etfa_j+1\le q'\le q}} W^{c}_{j,k,t,q'}$$

$$\forall\, j,k,t,q : (j,k,t,q) \in TRUCKN \text{ and } k \notin K^1 \quad (15)$$

$$HOLD_{t,q} = HOLD_{t,q-1} + FT_{t,q-1} - \sum_{\substack{j,k: \\ (j,k,t,q-1)\in TRUCKN, \\ k \notin K^1}} FA_{j,k,t,q-1} \qquad \forall\ t,q:(q>q1) \qquad (16)$$

$$SHORT_{t,q} \geq safe * capt_t - HOLD_{t,q} \qquad \forall\ t,q \quad (17)$$

$$Y_{j,r,q} \in \{0,1\} \qquad \forall\ j,r,q: \exists i:(i,j)\in E \text{ and } (i,r,q)\in M \qquad (18)$$

$$X^h_{j,k,r,q,q'} \in \{0,1\} \qquad \forall\ j,k,r,q,q':(j,k,r,q,q')\in N \qquad (19)$$

$$X^c_{j,k,r,q,q'} \in \{0,1\} \qquad \forall\ j,k,r,q,q':(j,k,r,q,q')\in N \qquad (20)$$

$$W^h_{j,k,t,q} \in \{0,1\} \qquad \forall\ j,k,t,q:(j,k,t,q)\in TRUCKN \qquad (21)$$

$$W^c_{j,k,t,q} \in \{0,1\} \qquad \forall\ j,k,t,q:(j,k,t,q)\in TRUCKN \qquad (22)$$

$$FA_{j,k,t,q} \geq 0 \qquad \forall\ j,k,t,q:(j,k,t,q)\in TRUCKN \qquad (23)$$

$$REFUEL_{t,q} \in \{0,1\} \qquad \forall\ t,q \quad (24)$$

$$SHORT_{t,q} \geq 0 \qquad \forall\ t,q \quad (25)$$

$$HOLD_{t,q} \geq 0 \qquad \forall\ t,q \quad (26)$$

$$FT_{t,q} \geq 0 \qquad \forall\ t,q \quad (27)$$

6. Discussion

The objective function maximizes a series of rewards while it minimizes penalties that reflect the quality of NAS Lemoore’s combined daily flight schedule. The user can modify the rewards and penalties through MSISCHE’s interface. Some time-based penalties are also computed within GAMS (GAMS, 2015). The first and second parts of the objective function include the rewards and penalties for aircraft conducting hot and cold refueling, respectively. These portions reward those aircraft which belong to events that were requested in the input flight schedules and are still included in the optimal solution, and they penalize aircraft for taking off at a different time than desired, and also aircraft that waited for refueling after landing. The last part of the objective function reflects the penalty for trucks being below their safety level of fuel.

Constraint set (1) guarantees the time uniqueness of the events by requiring that each aircraft *k* of event *j* going to range *r* does not get more than one time period *q* to take off and one time period q' to start refueling, either hot or cold. Constraint set (2) ensures that the total number of aircraft conducting hot refueling does not exceed the percentage of hot refueling allowed. Constraint set (3) ensures that each range or MOA *r*, except those in set R^1, is not assigned to more than one event *j* or joint mission in time period *q*. Constraint set (4) pertains to joint missions; it makes sure that all aircraft going to a joint mission take off at the same time period *q* and fly to the same range *r*. Constraint set (5) ensures that all aircraft of event *j* take off at the same time period *q* and go to the same range *r*, but they could refuel at different time period q'. Constraint sets (6) and (7) assign truck *t* to aircraft *k* at time q' to start refueling, hot and cold respectively. Constraint set (8) ensures that each truck *t* performs at most one activity in each time period. Constraint set (9) limits, at every time period *q*, the number of cold refueling aircraft to the capacity of cold refueling stations. Constraint set (10) prevents the number of hot refueling aircraft from exceeding the capacity of hot refueling stations in any time period. Constraint set (11) ensures that the number of trucks being used, at any time period *q*, do not exceed the number of available drivers. Constraint set (12) fixes a truck's starting fuel to be equal to its fuel capacity. Constraint set (13) prevents truck *t* from exceeding its fuel capacity at any time period *q*. Constraint set (14) allows truck *t,* at any time period *q*, to get fuel without exceeding its fuel capacity; a truck can also receive fuel before coming back from maintenance. Constraint set (15) calculates how much fuel truck *t* transfers to aircraft *k* during cold refueling at time period *q*. Constraint set (16) computes the amount of fuel that truck *t* holds at any time period *q.* Constraint set (17) models the fuel safety levels of the trucks. Constraint sets (18) to (27) define decision variable domains.

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IV. ANALYSIS AND RESULTS

We now exercise MSISCHE to study its performance in various scenarios, each with a unique configuration of squadrons and their respective daily flight schedules. In order to conduct sensitivity analysis, 400 scenarios were generated to simulate aircraft landing and refueling at NAS Lemoore.

A. DATA

All data was provided by CSFWP and NAS Lemoore Fuels Division. NAS Lemoore has a total of 5 double fuel skids (10 hot pits) for conducting hot refueling, drivers for conducting both types of refueling, and 11 fuel trucks for conducting cold refueling and as a means of transportation for refueling personnel to conduct hot refueling.

1. Squadrons

NAS Lemoore currently has 16 fighter squadrons: VFA-122, VFA-2, VFA-14, VFA-22, VFA-25, VFA-41, VFA-86, VFA-94, VFA-97, VFA-113, VFA-137, VFA-146, VFA-147, VFA-151, VFA-154, and VFA-192. To conduct sensitivity analysis, a symbolic squadron VFA-999 is added to this list.

2. MOA/Ranges

Aircraft conducting events departing from NAS Lemoore may be scheduled to fly to any MOA/range included in the NAS Lemoore inflight guide (CSFWP, 2016).

3. Fuel Skids

The fuel skids, used to conduct hot refueling, are available during specific hours set by NAS Lemoore Fuels Division. Hot refueling usually goes from 0800 to 2300 Monday through Thursday and from 0800 to 1600 on Friday. Each fuel skid is preassigned to specific squadrons based on proximity to the squadrons' maintenance facility. Cold refueling is conducted at the ramp, which is also close to the squadron's maintenance facility. Table 1 shows these assignments, and Figure 6 displays the locations of hot pits and ramps for hot and cold refueling respectively.

Table 1. Ramps and Fuel Skids Assignments

Ramp	1	2	3	4	5
Hot Pits	1 & 2	3 & 4	5 & 6	7 & 8	9 & 10
Squadrons	VFA-122	VFA-14	VFA-146	VFA-2	VFA-137
		VFA-97	VFA-147	VFA-22	VFA-86
		VFA-25	VFA-192	VFA-154	
		VFA-113	VFA-151	VFA-41	
			VFA-94		

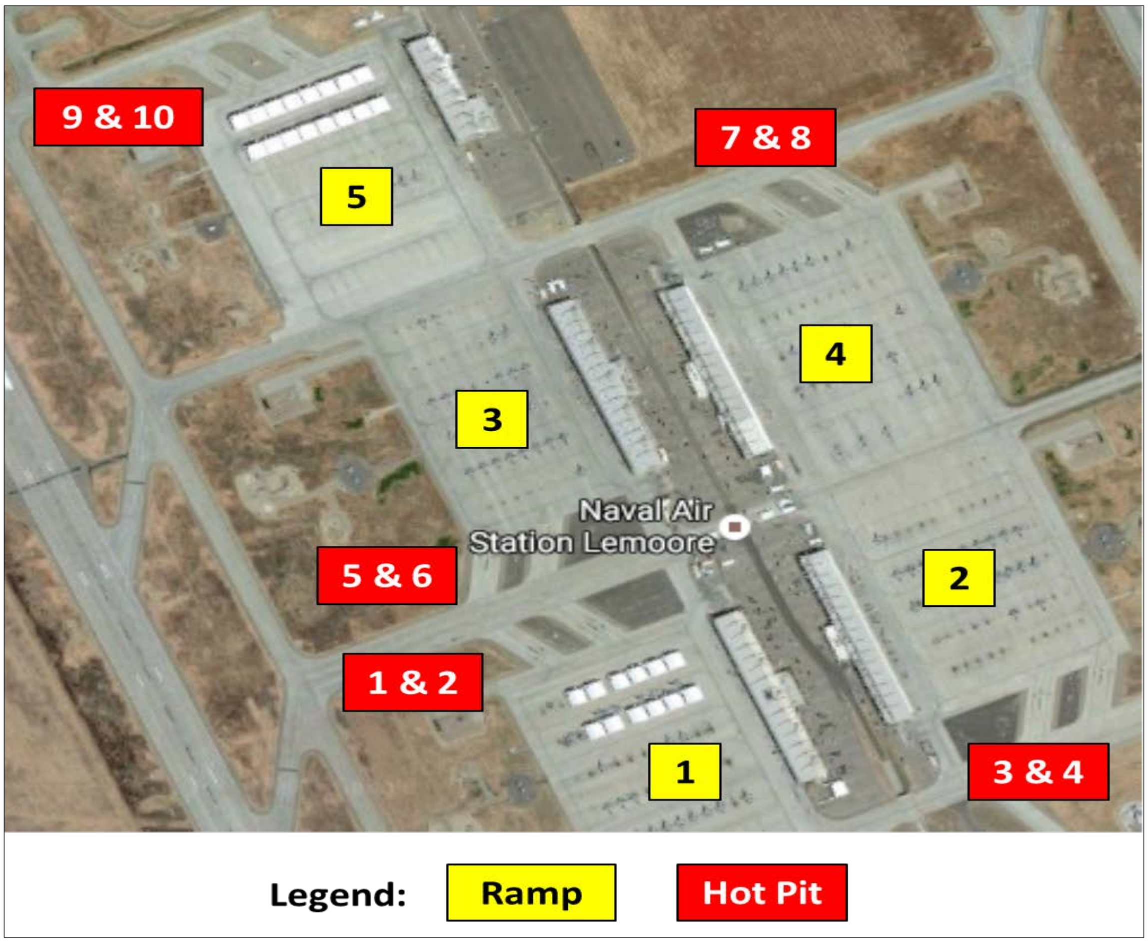


Figure 6. Ramp and Hot Pit Locations

4. Drivers

The drivers' work schedule is distributed in four shifts provided by NAS Lemoore Fuels Division; thus, the number of drivers varies during the day. Even though refueling is the drivers' primary duty, they have other tasks to complete such as cargo handling and sweeping runways, taxiways, and ramps. Figure 7 displays the distribution of drivers per hour, and Table 2 summarizes the number of drivers per shift assignment.

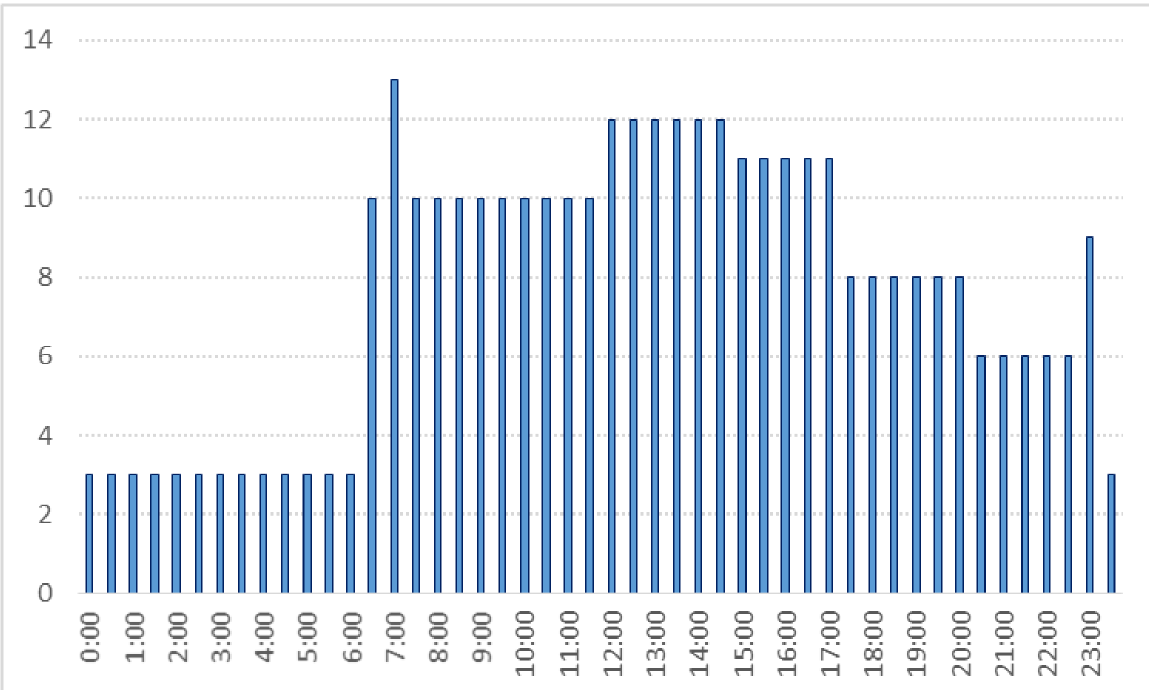


Figure 7. Distribution of Drivers per Hour

Table 2. Assignment of Drivers per Shift

Shift	1st shift (0630–1500)	1st shift late (0700–1530)	2nd shift (1200–2030)	3rd shift (1500–2330)	4th shift (2300–0730)
Drivers	7	3	2	6	3

5. Trucks

The number of trucks, currently 11, remains constant until one becomes unavailable because of breaking down or refueling its own tank. The fuel capacities of the trucks are 10,000 (10 trucks) or 8,000 (1 truck) gallons. The safety level to be refueled, currently 20%, is set by NAS Lemoore Fuels Division and remains constant. All available trucks can be used if there are enough drivers.

6. Penalties and Rewards

MSISCHE uses penalties and rewards to find the combined flight schedule’s optimal solution. Penalties and rewards are assigned to squadrons based on their priority or proximity to being deployed. The penalty is used to weight the aircraft refueling wait time and the modification of the events’ takeoff time. Table 3 displays the values assumed for priorities and penalties, in which VFA-122 has the highest values as the training fighter squadron.

Table 3. Priorities and Penalties Assigned to Squadrons

Squadron	VFA-122	VFA-2	VFA-14	VFA-22	VFA-25	VFA-41	VFA-86	VFA-94	VFA-97	VFA-113	VFA-137	VFA-146	VFA-147	VFA-151	VFA-154	VFA-192
Priority	20	19	18	17	16	1	1	1	1	1	1	1	1	1	1	1
Penalty	10	5	5	5	5	1	1	1	1	1	1	1	1	1	1	1

B. SCENARIO DEVELOPMENT

The scenarios are simulated using Microsoft Excel VBA code (Microsoft, 2013). The VBA scenario developer will be referenced as "Generator."

1. Assumptions

Besides the assumptions previously described in Section II.B.4, Generator assumes the following in order to produce a realistic scenario that provides the input data to the optimization model and heuristics:

- Some of NAS Lemoore fighter squadrons are deployed. To simulate this, the user defines the minimum of squadrons to fly, and Generator randomly selects a number of flying squadron between that minimum and the total of squadrons at NAS Lemoore.
- The training squadron, VFA-122, gets between 5 and 30 flight events daily. Other squadrons, selected to fly, have between 2 and 8 flight events. The number of flight events for each squadron is selected uniformly at random using these lower and upper bounds.
- The number of daily joint missions is approximately 5% of the total of flying events for that date.
- The number of events going to a joint mission could be 2 or 3, with 75 and 25 percent probability respectively.
- As in MSISCHE, squadrons receive deterministic priorities that are set by CSFWP.
- Assignment of MOA/ranges is based on the probability. Range R_2508 gets 50% of the events.
- The length of an event, from its takeoff time to its landing time, follows a discrete uniform distribution of 15-minute increments and could be as little as 30 minutes or up to 2 hours.
- The number of aircraft, or sorties, going to an event follows a discrete uniform distribution and could be between 1 and 5.
- The probability of an aircraft going to fly again after being refueled is based on its landing time. The landing times are separated in six groups: before 1500, between 1500 and 1700, between 1700 and 1900, between 1900 and 2100, between 2100 and 2200, and after 2200. The probabilities

for each group are 0.9, 0.7, 0.5, 0.3, 0.1, and 0, respectively. Whether or not an aircraft flies again is independent from aircraft to aircraft.

- Considering the monthly allowed hot refueling percentage, and using the assumed probabilities that an aircraft could be flying again after refueling, Generator designates if the aircraft will need hot or cold refueling.

- At most, one truck can be out of service and in maintenance on any day. If the scenario includes a breakdown, the truck is randomly selected out of the 11 trucks.

- Events' takeoff times are generated using a discrete uniform distribution of 15-minute increments from the time KNLC is open to an hour before KNLC is closed.

2. Scenario Generator

The workbook Generator creates each scenario by filling out the spreadsheets, exporting the spreadsheets as CSV files, executing MSISCHE's GAMS portion using the CSV files as input, and importing the results into a spreadsheet of the same workbook. Displayed in Figure 8 is the main screen of Generator. Besides allowing modification of parameter values to configure the scenarios, Generate also offers five choices to produce and run the scenarios: Generate Scenarios & Run MSISCHE (N), Generate Scenarios & Run MSISCHE (All), Generate Scenarios & Run Modified, Generate Scenarios & Run Current, and Generate Scenarios & Run all 3.

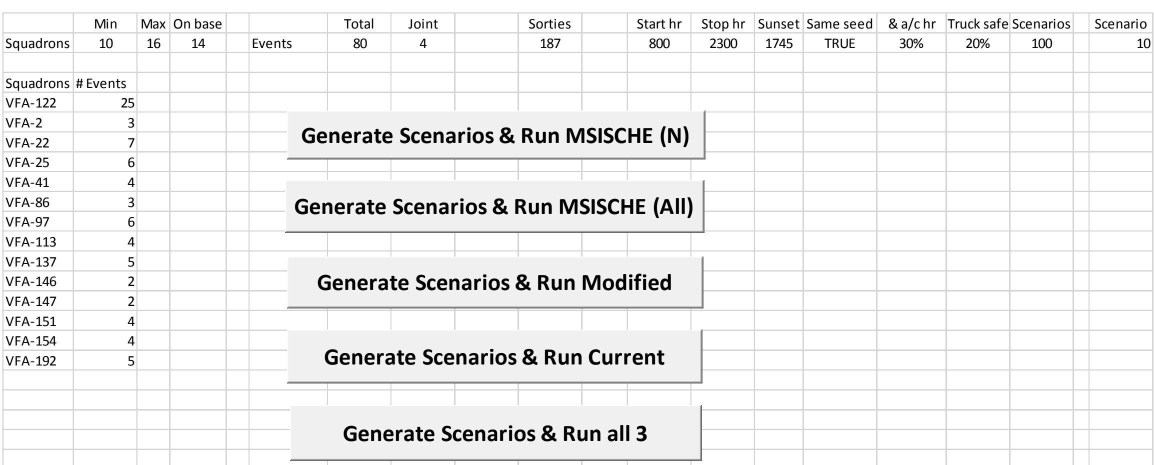


Figure 8. Snapshot of Generate, the Main Sheet of Generator

The first choice generates all the scenarios annotated under the Scenarios cell, but it only runs MSISCHE using the data of the last scenario. This option is useful to review the details of each event and each aircraft of the combined flight schedule solution. Figure 9 depicts a portion of the results of a scenario after using this choice. G T-Off and G Land are the takeoff and landing times generated-requested in the squadron's flight schedule, while M T-Off and M Land correspond to the takeoff and landing times recommended by MSISCHE. The Refuel cell indicates when the aircraft will refuel, having the minimum wait time after its landing.

Event	Aircraft	Range	G T-Off	G Land	M T-Off	M Land	Refuel	Hot/Cold
V122-e1	V122-a1	R_2508	830	930	830	930	930	Hot
V122-e1	V122-a2	R_2508	830	930	830	930	930	Cold
V122-e2	V122-a7	FCLP	845	915	845	915	915	Cold
V122-e3	V122-a8	R_2508	800	845	800	845	845	Hot
V122-e4	V122-a9	FCLP	800	845	800	845	845	Cold
V122-e4	V122-a10	FCLP	800	845	800	845	845	Hot
V122-e5	V122-a11	W_283	815	900	815	900	915	Cold
V122-e5	V122-a12	W_283	815	900	815	900	900	Hot
V14-e1	V14-a1	Fallon_B17	945	1030	945	1030	1045	Hot
V14-e1	V14-a2	Fallon_B17	945	1030	945	1030	1145	Cold
V14-e2	V14-a3	Lemoore_A	930	1015	945	1030	1030	Hot
V14-e2	V14-a4	Lemoore_A	930	1015	945	1030	1115	Cold
V22-e2	V22-a5	R_2508	1445	1515	1445	1515	1515	Hot
V22-e2	V22-a6	R_2508	1445	1515	1445	1515	1700	Cold
V22-e3	V22-a7	FERRY	2215	2300	2230	2315	2330	Cold
V22-e3	V22-a8	FERRY	2215	2300	2230	2315	2330	Cold
V25-e1	V25-a2	FCLP	1245	1315	1245	1315	1315	Hot
V25-e1	V25-a3	FCLP	1245	1315	1245	1315	1345	Cold
V25-e2	V25-a4	Superior_Valley	1315	1400	1315	1400	1415	Cold
V25-e2	V25-a5	Superior_Valley	1315	1400	1315	1400	1430	Cold
V25-e3	V25-a7	W_291	1315	1400	1315	1400	1445	Cold

Figure 9. Snapshot of a Portion of Scenario_Results Sheet from Generator

The second choice creates all the scenarios requested under the Scenarios cell and runs MSISCHE using the data of each scenario. This option is useful to review the summary of the combined flight schedule solution. Figure 10 depicts the results after selecting this choice with several scenarios. The report includes number of events and aircraft given, flying, and landing in KNLC; it also summarizes, separately for hot and cold refueling, the total number of aircraft conducting each type of refueling, the number of aircraft waiting to be refueled, the total refueling wait time by all aircraft, and the maximum time an aircraft has to wait to be refueled. Additionally, this report presents other values related to MSISCHE's performance such as the percentage of hot refueling aircraft obtained, the model and solver status, the upper bound and found solutions, and the execution elapsed time.

Scenario	Events Given	Events Flying	Events la KNLC	Sorties Given	Sorties Flying	Sorties la KNLC	Hot Ref Total AC	Hot Ref AC wait	Hot Ref Total Wait	Hot Ref Max AC Wait	Cold Ref Total AC	Cold Ref AC wait	Cold Ref Total Wait	Cold Ref Max AC Wait	hot ref %	Model Status	Solver Status	Best Possible	MIP Solution	Relative Gap	Elapsed Time
1	86	86	83	210	210	204	61	0	0	0	143	56	3000	240	29.90%	8	3	1946.95	1946.87	0.00%	3623.91
2	68	68	62	158	158	147	44	0	0	0	103	31	1800	180	29.93%	1	1	1271.95	1271.95	0.00%	49.53
3	52	52	51	121	121	120	36	0	0	0	84	10	195	30	30.00%	1	1	1045.98	1045.98	0.00%	29.83
4	57	57	56	112	112	109	32	0	0	0	77	21	720	90	29.36%	1	1	1177.81	1177.81	0.02%	25.79
5	63	63	60	136	136	129	38	0	0	0	91	25	570	45	29.46%	1	1	974	974	0.00%	51.53
6	71	71	67	156	156	144	43	0	0	0	101	32	1905	150	29.86%	1	1	1350.82	1350.82	0.01%	67.3
7	54	54	54	122	122	122	36	0	0	0	86	32	2085	165	29.51%	1	1	875.51	875.51	0.06%	79.75
8	78	78	77	160	160	156	46	0	0	0	110	31	1080	105	29.49%	1	1	1484.9	1484.9	0.01%	139.47
9	76	76	71	167	167	158	47	0	0	0	111	43	3945	255	29.75%	1	1	1359.17	1359.17	0.01%	108.77
10	80	80	76	187	187	178	53	0	0	0	125	55	2430	195	29.78%	8	3	1813.59	1813.59	0.02%	3619.5

Figure 10. Snapshot of Summarized Results after Using the Second Choice of Generator

The module also implements two heuristic approaches: the “current refueling policy” and the “modified refueling policy.” The current refueling policy is designed to mimic the current practice at NAS Lemoore, while the modified policy models a slight relaxation of the current policy which MSISCHE also models. Both heuristics handle takeoff requests in order of priority. The highest priority event is examined first given its requested takeoff time. As lower priority events are examined, they may be asked to wait for takeoff if they conflict with higher-priority events that are already assigned to the same MOA/range. Once the takeoff schedule is determined, the heuristics determine when refuelings will occur. Although takeoffs are assigned according to priority, landings are done on a first-come, first-served basis. In the current policy, each aircraft is only allowed to use its preassigned hot pit; whereas in the modified policy, all aircraft are allowed to use any hot pit, as in MSISCHE. Under both policies, aircraft arriving for refueling enter a queue and are assigned to their respective hot pits as the pits become available. A pit may be unavailable because it is currently occupied by another aircraft or because no truck is available to service it. Both heuristics model the amount of fuel available in the trucks as in MSISCHE. For the current policy, each hot skid has its own queue. For the modified policy, there is only a single queue for all hot pits. The third and fourth choices of Generator produce all the scenarios annotated under the Scenarios cell and run the VBA code that simulates the modified and current aircraft refueling process at NAS Lemoore. Figures 11 and 12 show snapshots with the results for heuristics after selecting the third and fourth choices respectively.

Scenario	Events Given	Events la KNLC	Sorties Given	Sorties la KNLC	Hot Ref Total AC	Hot Ref AC waiting	Hot Ref Total Wait (m)	Hot Ref Max AC Wait (m)	Cold Ref Total AC	Cold Ref AC waiting	Cold Ref Total Wait (m)	Cold Ref Max AC Wait (m)	hot ref %
1	86	82	209	195	58	0	0	0	137	70	2205	75	29.74%
2	72	72	172	172	51	7	105	15	121	61	1950	75	29.65%
3	79	75	187	175	52	9	165	30	123	37	1155	60	29.71%
4	56	52	126	117	35	0	0	0	82	17	330	30	29.91%
5	65	61	161	152	45	2	30	15	107	33	570	30	29.61%
6	65	61	146	136	40	6	90	15	96	68	3030	75	29.41%
7	63	61	142	138	41	6	90	15	97	51	2355	75	29.71%
8	59	58	134	133	39	0	0	0	94	10	180	30	29.32%
9	65	63	152	147	44	0	0	0	103	10	210	30	29.93%
10	77	74	181	171	51	2	30	15	120	21	390	30	29.82%
11	68	65	164	160	48	7	105	15	112	70	2280	60	30.00%
12	81	79	203	199	59	2	30	15	140	91	3525	75	29.65%

Figure 11. Snapshot of Summarized Results for a Heuristic Solution after Using the Third Choice of Generator

Scenario	Events Given	Events la KNLC	Sorties Given	Sorties la KNLC	Hot Ref Total AC	Hot Ref AC waiting	Hot Ref Total Wait (m)	Hot Ref Max AC Wait (m)	Cold Ref Total AC	Cold Ref AC waiting	Cold Ref Total Wait (m)	Cold Ref Max AC Wait (m)	hot ref %
1	86	82	209	195	58	23	1185	105	137	118	6765	165	29.74%
2	72	72	172	172	51	14	450	60	121	92	7080	180	29.65%
3	79	75	187	175	52	11	390	60	123	107	7980	225	29.71%
4	56	52	126	117	35	13	435	60	82	58	2445	135	29.91%
5	65	61	161	152	45	10	240	60	107	76	3420	105	29.61%
6	65	61	146	136	40	15	675	75	96	73	6345	195	29.41%
7	63	61	142	138	41	8	210	45	97	72	4410	135	29.71%
8	59	58	134	133	39	4	75	30	94	59	2565	135	29.32%
9	65	63	152	147	44	10	345	60	103	57	1830	180	29.93%
10	77	74	181	171	51	18	420	45	120	87	4905	240	29.82%
11	68	65	164	160	48	13	420	60	112	89	8445	240	30.00%
12	81	79	203	199	59	15	330	45	140	122	9990	225	29.65%

Figure 12. Snapshot of Summarized Results for a Heuristic Solution after Using the Fourth Choice of Generator

The fifth choice calls choices two, three, and four; therefore, after generating all the scenarios requested, this choice executes and summarizes the results of using MSISCHE, the VBA code with modified refueling policy, and the VBA code with current refueling policy.

C. SENSITIVITY ANALYSIS

To conduct sensitivity analysis, we evaluated the results of 400 scenarios with the fifth choice of Generator; thus, under the three main executions of Generator: using MSISCHE, using the VBA code to simulate the current refueling policy, and using the VBA to simulate the modified refueling policy. These 400 scenarios were distributed as follows: 100 scenarios use the current setup of squadrons and refueling resources, and assumptions previously stated in Section II.B.4; 100 scenarios utilize the same setup but add a squadron; 100 scenarios use the original setup but with one less truck; and 100 scenarios utilize the same basic setup but with one less driver. Even though an optimization model provides the value of its objective function, the sensitivity analysis was focused on figures of merit such as maximum and average aircraft refueling wait time, number of aircraft waiting to be refueled, and frequency of refueling wait time, all measured during both hot and cold refueling.

Each of our scenarios applied to MSISCHE was generated and computed using a Dell, Precision T7910 computer with two Intel® Xenon® CPU E5-2699 @2.3GHz processors, 128 GB of RAM installed and running the Windows 7 Professional operating system (Microsoft, 2009). The program software used for the optimization is GAMS 24.4.2 utilizing CPLEX solver (GAMS, 2015). With these conditions our model typically contains approximately from 45,397 to 113,674 constraints and from 122,911 to 346,881 decision variables, of which 89,085 to 923,222 decision variables are integer. Solution times vary for each scenario; Figure 13 depicts a histogram with the time used to solve a scenario using MSISCHE with five and zero percent optimality gaps. Figure 13 and subsequent figures are developed using Microsoft Excel (Microsoft, 2013).

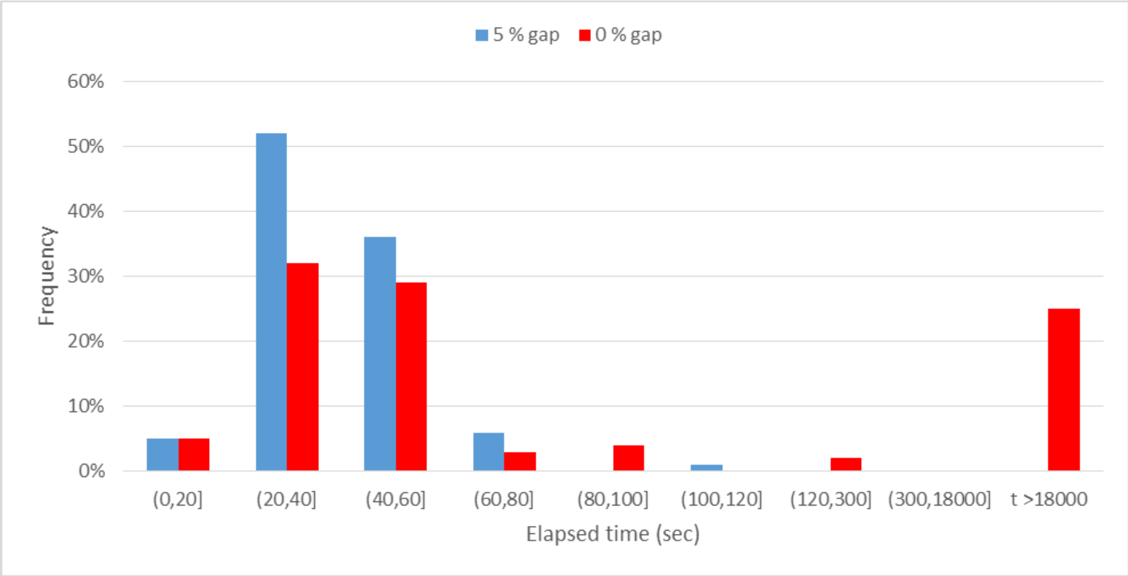


Figure 13. Frequency of Solution Times Used by MSISCHE over All Scenarios with 0% and 5% Optimality Gaps

1. Using Current Squadrons and Refueling Resources

Figures 14 through 17 present the comparisons, in regards to hot refueling wait time, among the three executions of Generator after running the 100 scenarios produced using the current squadrons, current refueling resources, and assumptions. Figure 14 shows the difference in the maximum wait time that aircraft have to incur to conduct hot refueling. Figure 15 displays the comparison of the average aircraft wait time before hot refueling. Figure 16 illustrates the number of aircraft that waited to conduct hot refueling. Figure 17 displays a comparison of histograms with the frequency of waiting time that aircraft experience before receiving hot refueling over all scenarios.

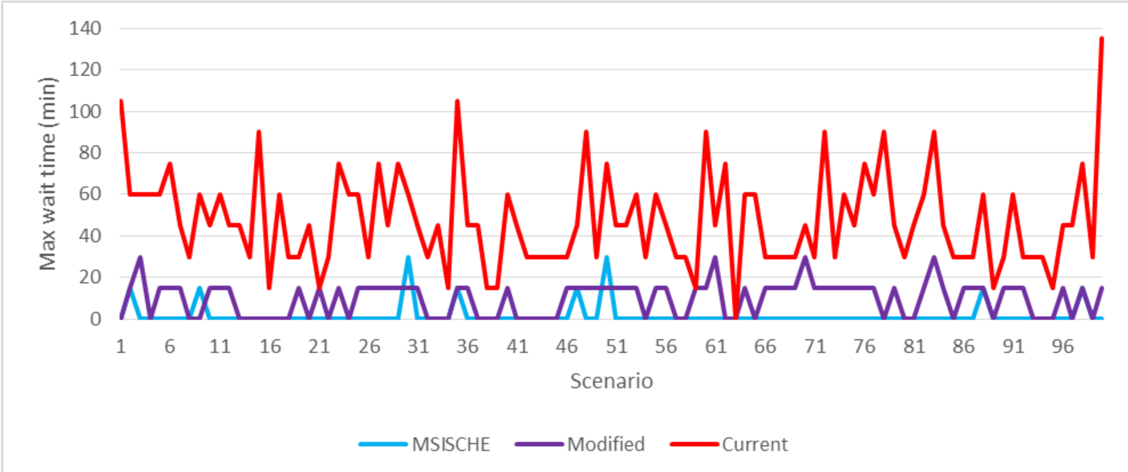


Figure 14. Maximum Wait Time to Conduct Hot Refueling in 100 Scenarios with Current Squadrons and Refueling Resources

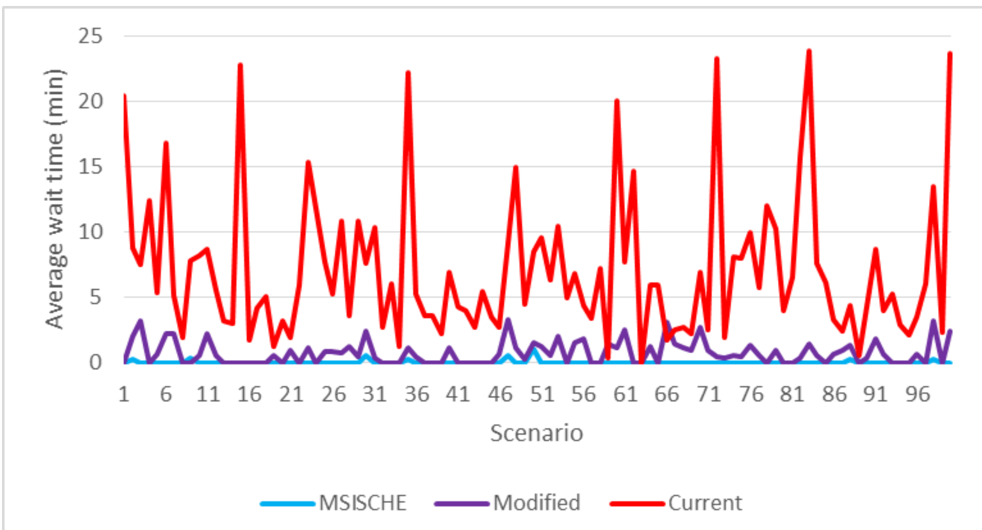


Figure 15. Average Wait Time to Conduct Hot Refueling in 100 Scenarios with Current Squadrons and Refueling Resources (Averaged over all Flights)

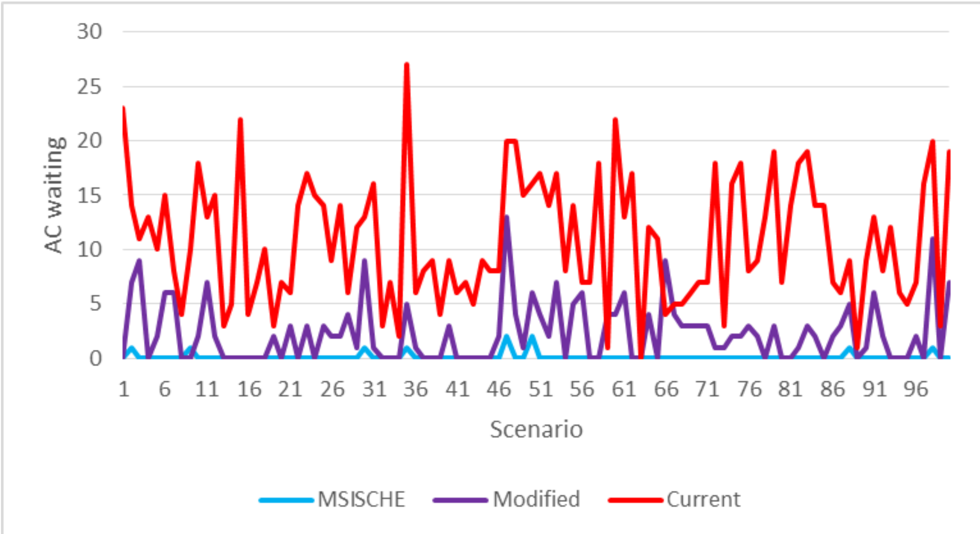


Figure 16. Number of Aircraft Waiting to Conduct Hot Refueling in 100 Scenarios with Current Squadrons and Refueling Resources

The following histogram compares the hot refueling wait time when aircraft follow the three alternatives of flight and refueling schedules: flight and refueling schedules obtained from MSISCHE, flight schedule generated-requested by Generator and refueling schedule per current refueling policy, and flight schedule generated-requested by Generator and refueling schedule per modified refueling policy.

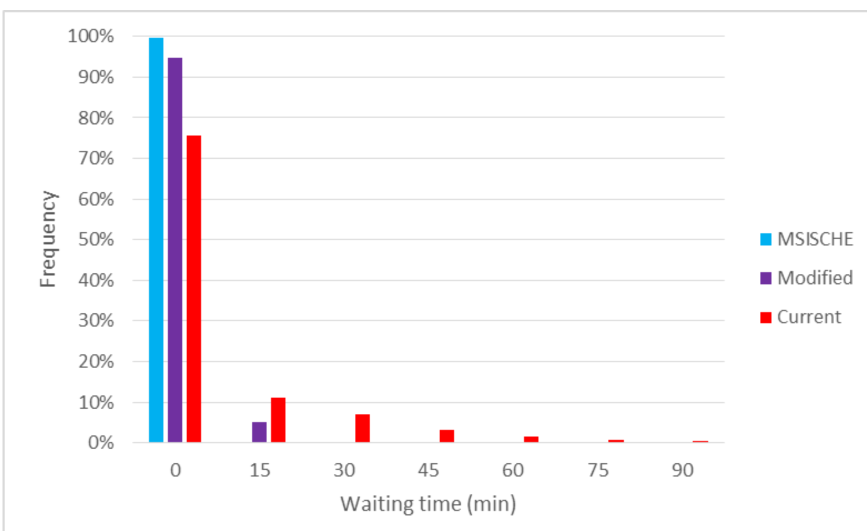


Figure 17. Frequency of Hot Refueling Wait Time over 100 Scenarios with Current Squadrons and Refueling Resources

These previous four figures indicate a large difference in values during hot refueling between aircraft that land per the generated-requested flight schedules and refuel according to the current and modified refueling policies against aircraft that land and refuel according to MSISCHE’s schedule. Additionally, these graphs show that, using the generated-requested flight schedules, their values improve by just using the modified instead of the current refueling policy; however, those values improve even more when aircraft follow MSISCHE’s schedule. The values of maximum aircraft refueling wait time, average aircraft refueling wait time, and number of aircraft waiting for hot refueling is small in most of the scenarios when following MSISCHE’s solution. On average, these values were reduced by 96.9%, 99.5%, and 99.1%, respectively when using MSISCHE instead of the current refueling policy. Figure 14 indicates that, in some scenarios, the maximum aircraft refueling wait time following MSISCHE might be higher than when using the modified refueling policy, but the average wait time and number of aircraft waiting are lower using MSISCHE. This happens because the objective value of MSISCHE minimizes the waiting time over all aircraft, not just for one.

Since hot refueling wait time is more expensive than cold, the main objective of MSISCHE is to minimize the hot refueling wait time. A secondary objective of MSISCHE is to minimize the cold refueling wait time without jeopardizing the hot refueling wait time. Similar results for cold refueling appear in Figures 18 through 21. Figure 18 shows the difference in the maximum wait time that aircraft have to incur to conduct cold refueling. Figure 19 compares the average aircraft wait time before cold refueling. Figure 20 illustrates the number of aircraft that waited to conduct cold refueling. Figure 21 displays a comparison of histograms with the frequency of waiting time that aircraft experience before receiving cold refueling.

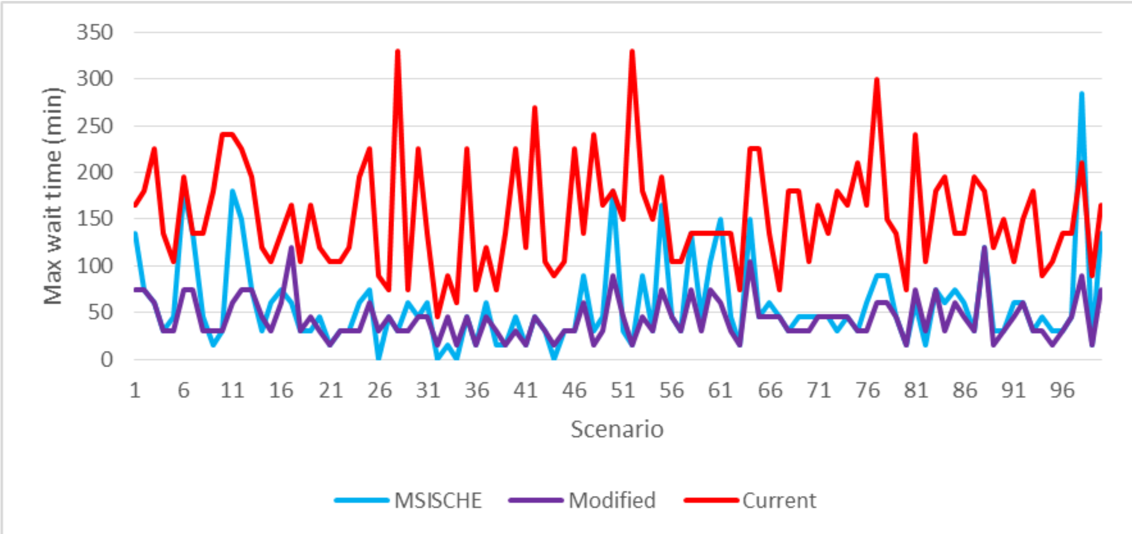


Figure 18. Maximum Wait Time to Conduct Cold Refueling in 100 Scenarios with Current Squadrons and Refueling Resources

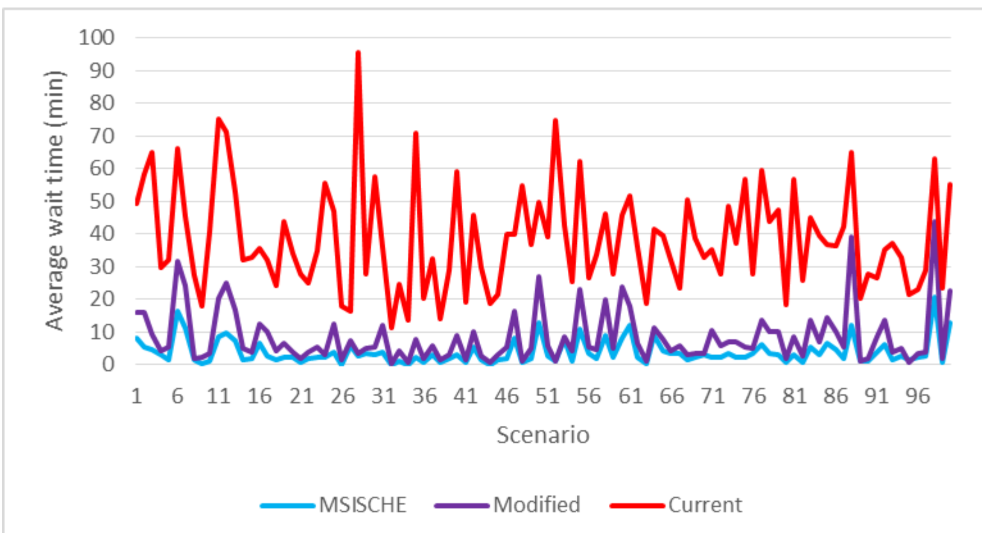


Figure 19. Average Wait Time to Conduct Cold Refueling in 100 Scenarios with Current Squadrons and Refueling Resources (Averaged over all Flights)

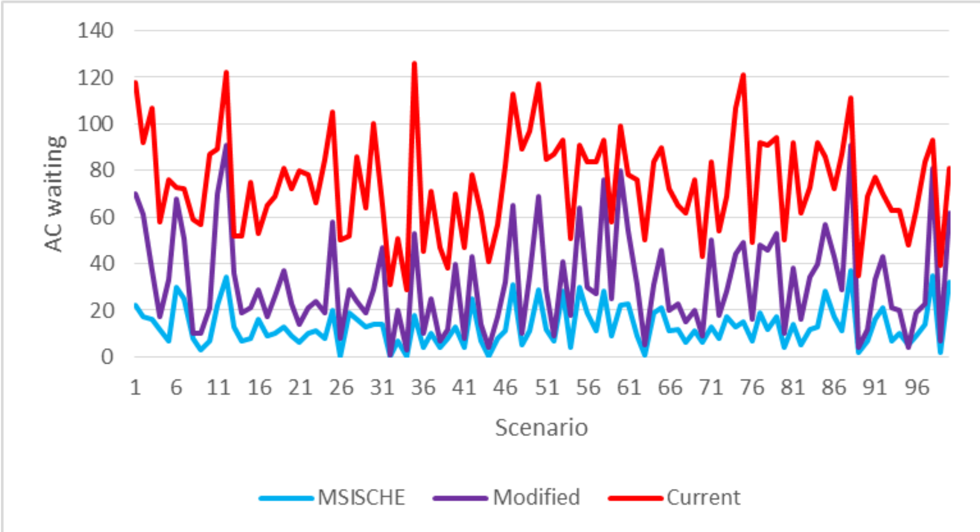


Figure 20. Number of Aircraft Waiting to Conduct Cold Refueling in 100 Scenarios with Current Squadrons and Refueling Resources

The following histogram compares the cold refueling wait time when aircraft follow the three variants of flight and refueling schedules.

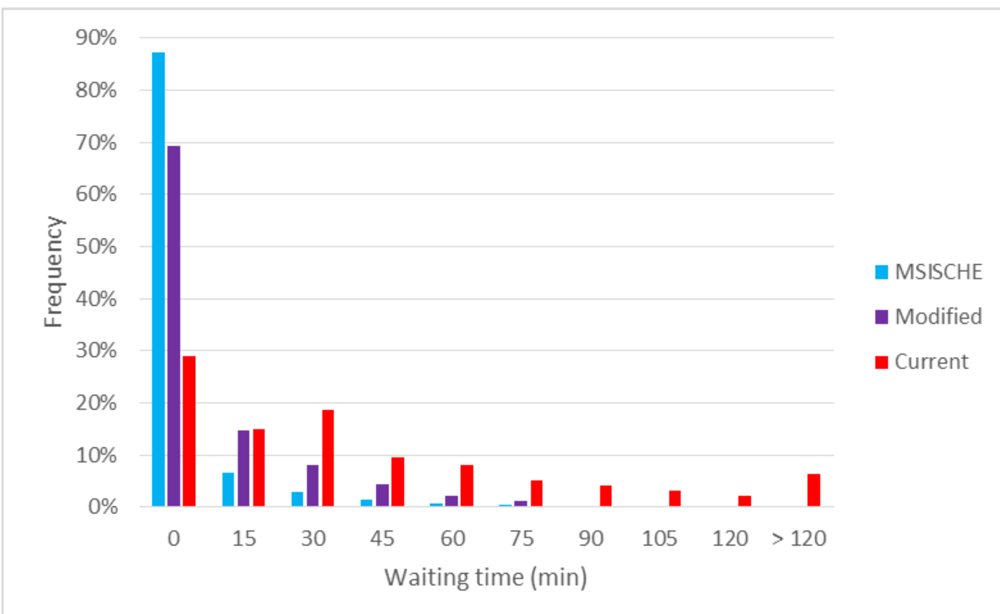


Figure 21. Frequency of Cold Refueling Wait Time over 100 Scenarios with Current Squadrons and Refueling Resources

These previous four figures indicate the differences in values during cold refueling between aircraft that land based on the generated-requested flight schedules and refuel according to the current and modified refueling policies against aircraft that land and refuel according to MSISCHE's schedule. Additionally, and following the same behavior with the hot refueling comparison, these graphs show that their values improve simply by using the modified instead of the current refueling policy; however, those values improve even more when following MSISCHE's schedule. On average, the values of maximum aircraft refueling wait time, average aircraft refueling wait time, and number of aircraft waiting for cold refueling improved by 62.7%, 90.1%, and 82.2%, respectively, when using MSISCHE rather than the current refueling policy. The values of average aircraft refueling wait time and number of aircraft waiting for cold refueling are lower in all the scenarios by following MSISCHE; however, the maximum aircraft refueling wait time, in some scenarios, might appear higher when using MSISCHE instead of the modified policy. This is explained by the objective value of MSISCHE which minimizes the waiting time over all aircraft.

Figure 22, from Gerber and Clark (2013), illustrates the number of aircraft arriving by day of the week and by time of the day. The peaks during certain hours, which can represent more than 15 arrivals, certainly increase the aircraft refueling demand. Having multiple arrivals at the same time is fine; however, sometimes these peak demands exceed the availability of refueling resources and cause high refueling wait time.

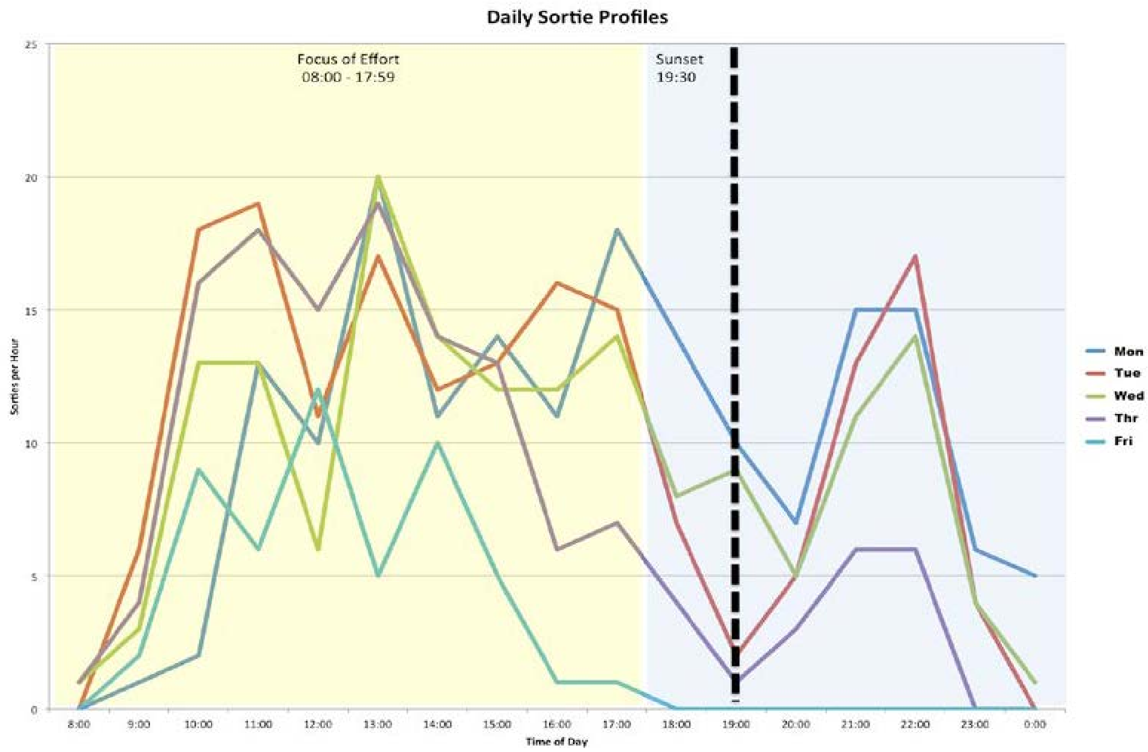


Figure 22. Daily Aircraft Arrival Patterns. Source: Gerber & Clark (2013).

MSISCHE's objective of minimizing the aircraft refueling wait time is obtained by leveraging the number of aircraft arrivals throughout the day. Comparisons of the number and time of aircraft arrivals are displayed in Figures 23 and 24. For a randomly selected scenario, Figure 23 shows the difference of aircraft arriving when they follow the generated-requested flight schedules provided from the scenario against aircraft arriving per the flight schedules obtained from MSISCHE.

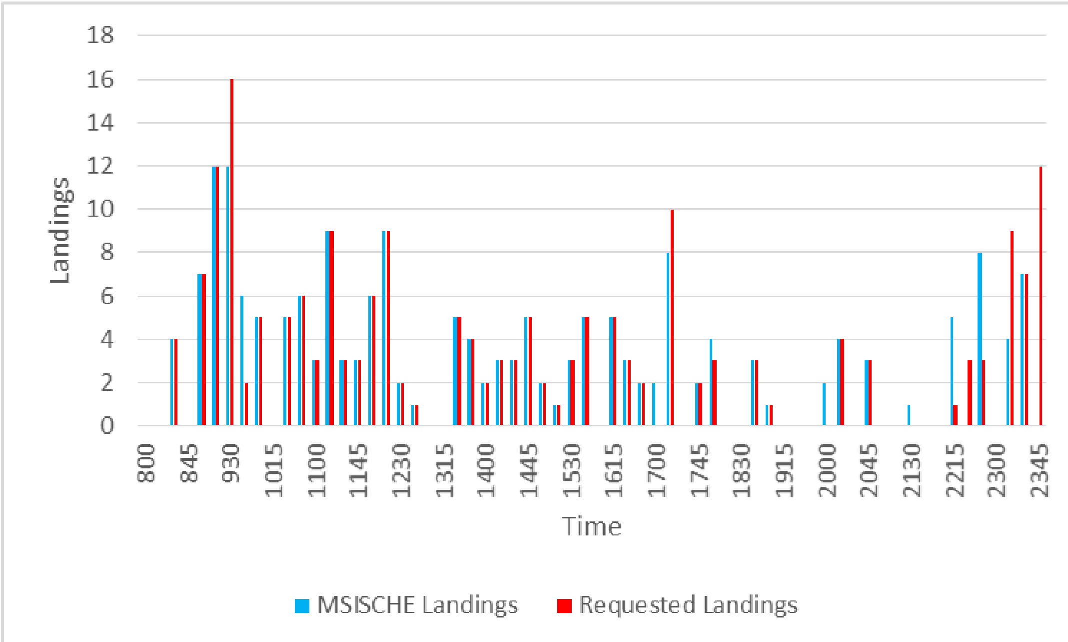


Figure 23. Number of Aircraft Landing during a Scenario when Aircraft Follow Takeoff from the Requested Flight Schedule and Takeoff Recommended by MSISCHE

For a randomly selected scenario, Figure 24 displays a radar-type comparison of the number and time of aircraft landing when aircraft follow the flight schedules from the scenario and the flight schedules obtained from MSISCHE against the refueling resources per time period. This graph illustrates the aircraft arrivals against the boundaries of number of drivers, number of trucks, and maximum number of refueling stations. The maximum number of refueling stations is computed by using the number of drivers, number of trucks, and number of hot skids. Because of the double capability of each hot skid, the number of aircraft arriving could exceed the number of drivers or trucks at any time period; however, in order to minimize the aircraft refueling wait time, the number of arrivals should not exceed the maximum number of refueling stations. The red line, which indicates the arrivals following the scenario's generated-requested flight schedules, sometimes surpasses the maximum number of stations' boundary. The blue dashed line, representing the arrivals per time period following MSISCHE's flight schedule, does not exceed this boundary.

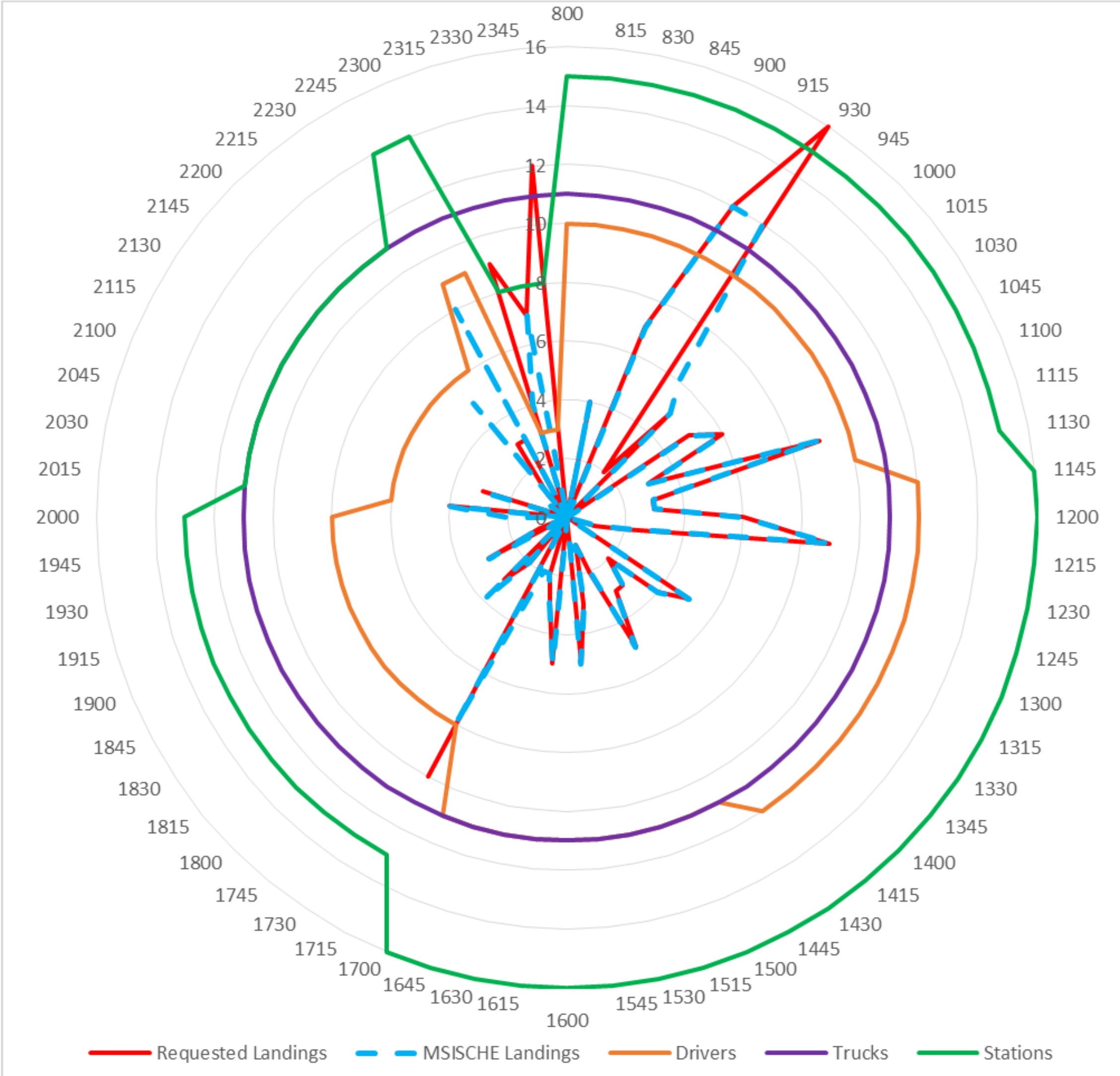


Figure 24. Aircraft Landings When Aircraft Follow Takeoff from the Requested Flight Schedule and Takeoff Recommended by MSISCHE against Drivers, Trucks, and Maximum Refueling Stations per Time Period

In order to increase the aircraft flying time available while preserving squadrons' authority and accountability, MSISCHE's optimal solution corresponds to a balance between the minimization of refueling wait time and minimization of deviation from the squadrons' proposed schedules. Figure 25 displays the percentage of events that changed their takeoff time in each scenario. On average, 97% of the squadron's requested flying times are followed. When MSISCHE suggests a change from the request, it is with the knowledge that the change is feasible based on MOA/range availability, the change is minimal, and the requests from the highest priority squadrons are protected.

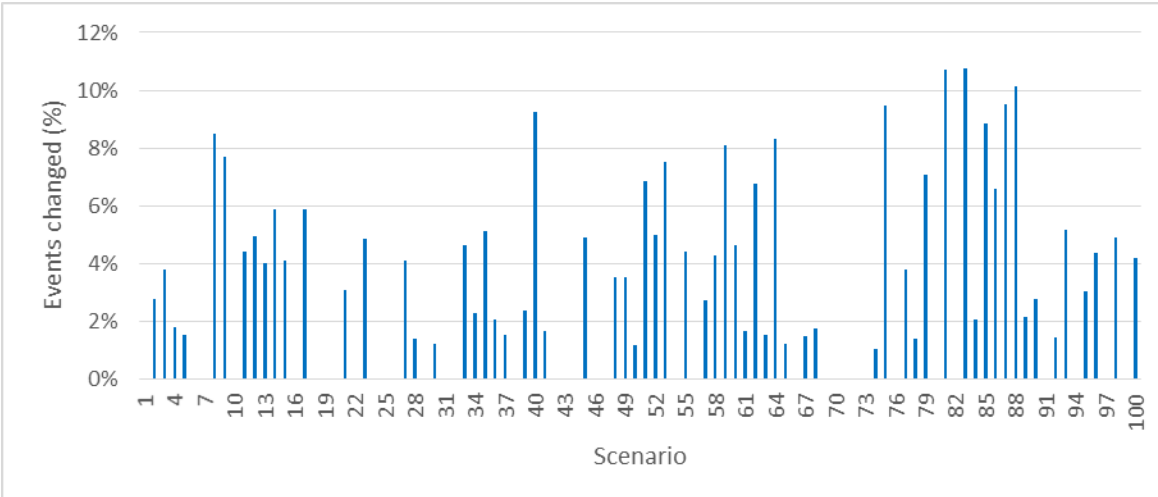


Figure 25. Percentage of Events Changed per Scenario

2. Adding One Squadron to the Original Setup

To simulate the arrival of the JSF to NAS Lemoore, a new squadron VFA-999 was added to the list of Lemoore home-based fighter squadrons. Per Lemoore Fuels Division, even though a JSF holds more fuel than an F-18, the average rate of fuel transfer to the JSF is about the same as that to an F-18; thus, refueling a JSF is expected to take longer.

Figures 26 through 29 present the comparisons, in regards to hot refueling wait time, among the three executions of Generator with the 100 scenarios produced after adding the JSF squadron. Figure 26 shows the difference in the maximum wait time that aircraft have to incur to conduct hot refueling. Figure 27 displays the comparison of the average aircraft wait time before hot refueling. Figure 28 illustrates the number of aircraft that waited to conduct hot refueling. Figure 29 compares the hot refueling wait time when aircraft follow the three alternatives of flight and refueling schedules. The UnA column in Figure 29 represents the 0.1% of unassigned sorties in MSISCHE's solution. Unassigned sorties occur because refueling demand cannot be adequately smoothed using at most a two-hour schedule shift in either direction to avoid refueling delays. These unassigned sorties reflect instances in which CSFWP cannot achieve the goal of short refueling wait times while also preserving a large degree of squadron-level autonomy. The two heuristic approaches do not result in unassigned aircraft because they allow arbitrarily long delays. However, in practice, refueling delays can cause cancellations if the aircraft is scheduled for another event before refueling can be completed; this is not reflected in our model. Figures 26 through 28 only display data pertaining to the aircraft that actually fly in each of the three executions (MSISCHE, modified refueling policy, and current refueling policy) and do not reflect the flights that are unassigned by MSISCHE.

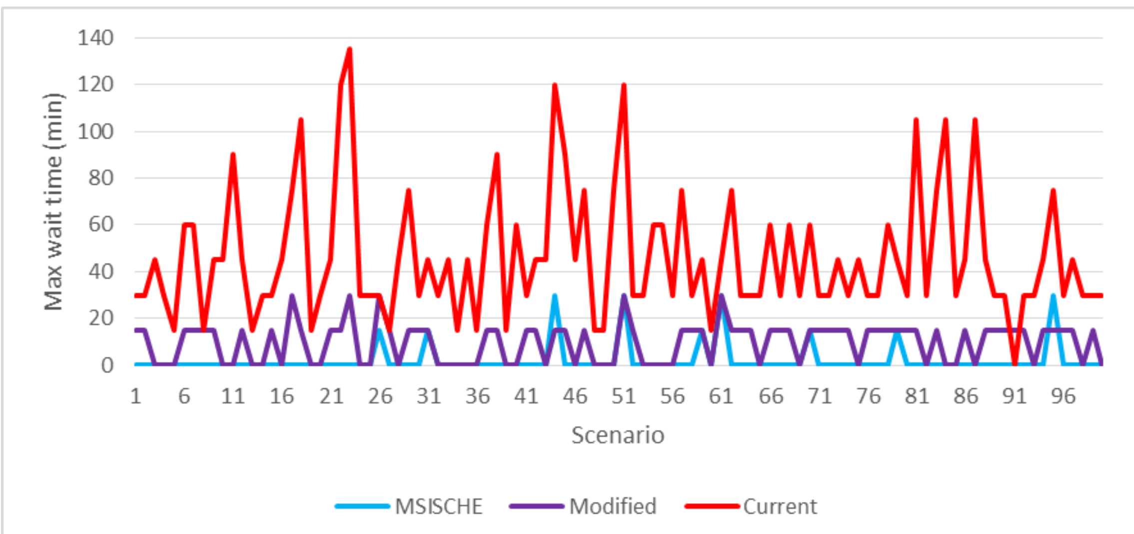


Figure 26. Maximum Wait Time to Conduct Hot Refueling in 100 Scenarios When Adding a Squadron to the Original Setup

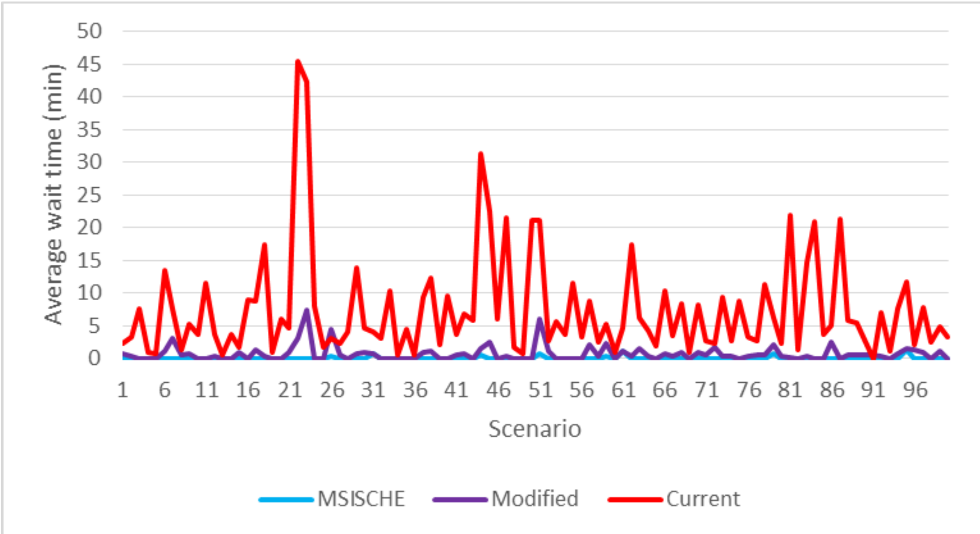


Figure 27. Average Wait Time to Conduct Hot Refueling in 100 Scenarios When Adding a Squadron to the Original Setup (Averaged over all Flights)

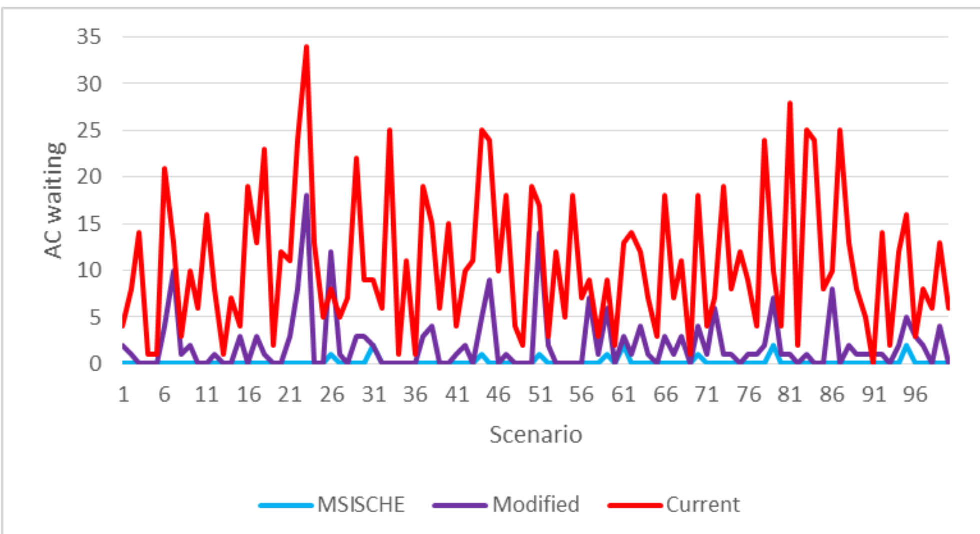
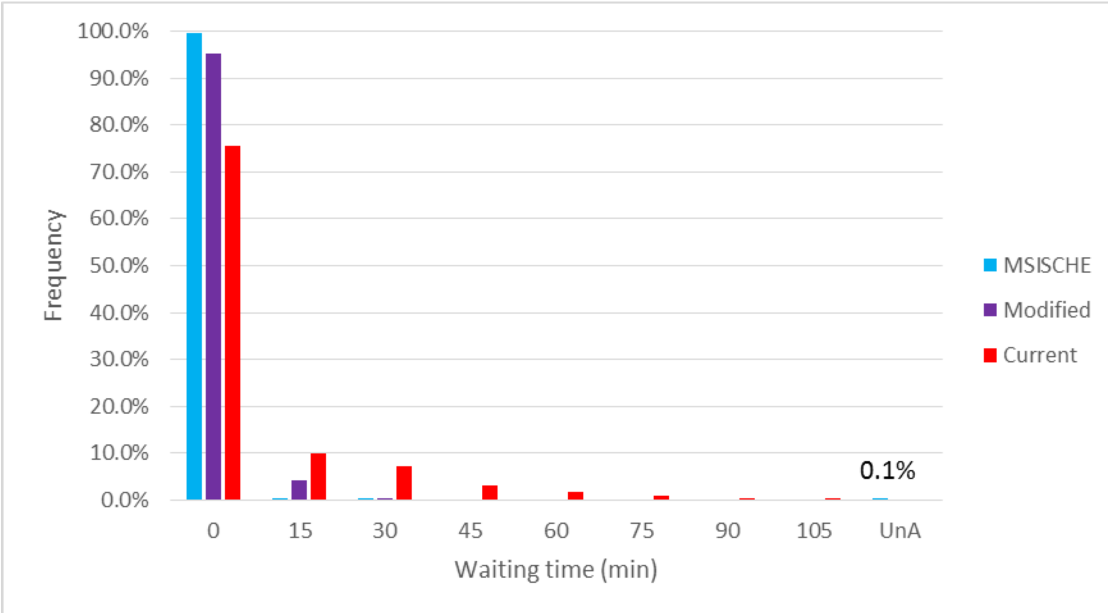


Figure 28. Number of Aircraft Waiting to Conduct Hot Refueling in 100 Scenarios When Adding a Squadron to the Original Setup



The far-right column represents the percentage of unassigned aircraft.

Figure 29. Frequency of Hot Refueling Wait Time over 100 Scenarios When Adding a Squadron to the Original Setup

These previous four figures indicate that the results of conducting hot refueling with the added squadron generally mirror those from conducting hot refueling with the baseline. On average, the value of average aircraft refueling wait time increased by 5% after adding the squadron; however, by using MSISCHE, this value is reduced by 99.2% for those events scheduled by MSISCHE. On average, the values of maximum aircraft refueling wait time and number of aircraft waiting for hot refueling, for those events scheduled by MSISCHE, improved by 95.8% and 98.8%, respectively, when following MSISCHE instead of the current refueling policy.

Similar results for cold refueling appear in Figure 30 through Figure 33. Figure 30 shows the difference in the maximum wait time that aircraft have to incur to conduct cold refueling. Figure 31 displays the comparison of the average aircraft wait time before cold refueling. Figure 32 illustrates the number of aircraft that waited to conduct cold refueling. Figure 33 compares the cold refueling wait time when aircraft follow the three variants of flight and refueling schedules. The UnA column represents the 0.1% of unassigned sorties or aircraft not included in MSISCHE's solution. Figures 30 through 32 only display data pertaining to the aircraft that actually fly in each of the three executions (MSISCHE, modified refueling policy, and current refueling policy).

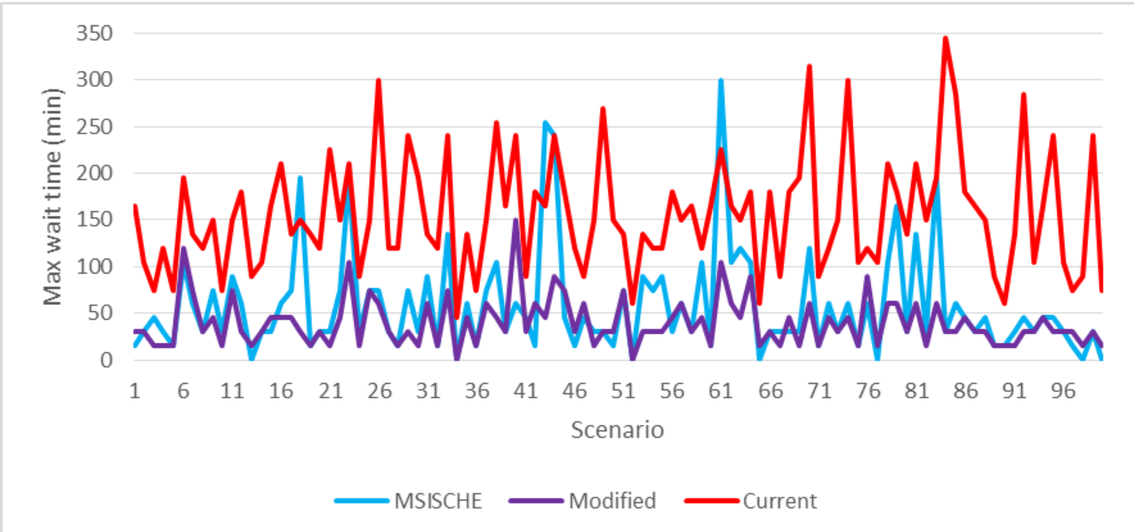


Figure 30. Maximum Wait Time to Conduct Cold Refueling in 100 Scenarios When Adding a Squadron to the Original Setup

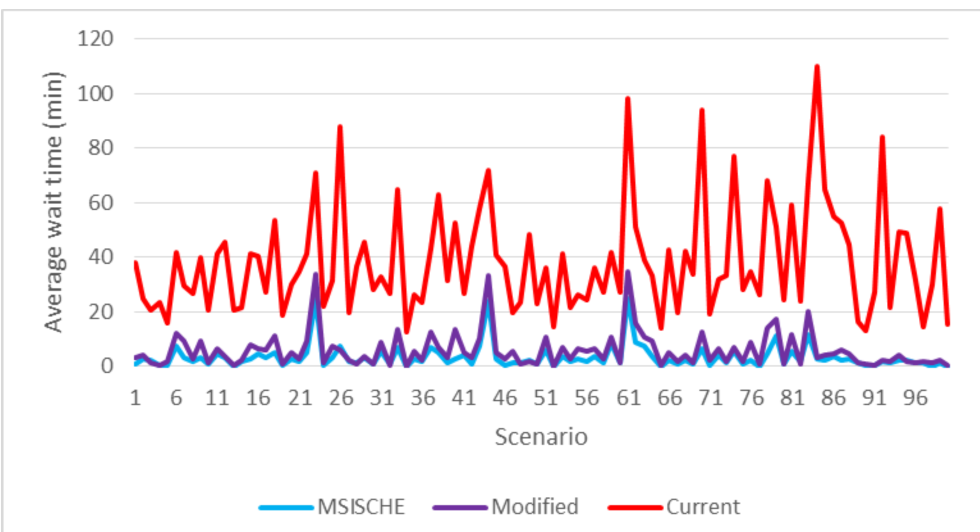


Figure 31. Average Wait Time to Conduct Cold Refueling in 100 Scenarios When Adding a Squadron to the Original Setup (Averaged over all Flights)

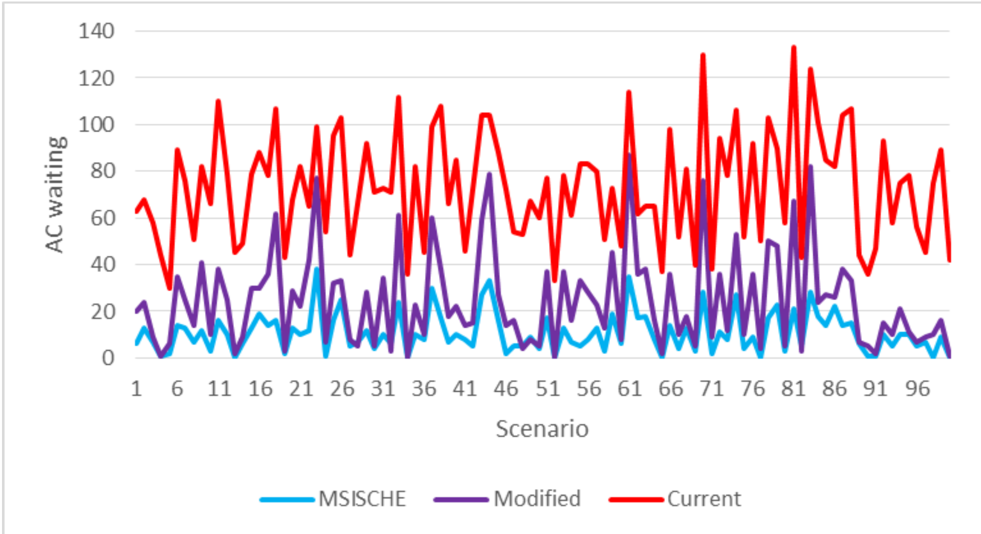
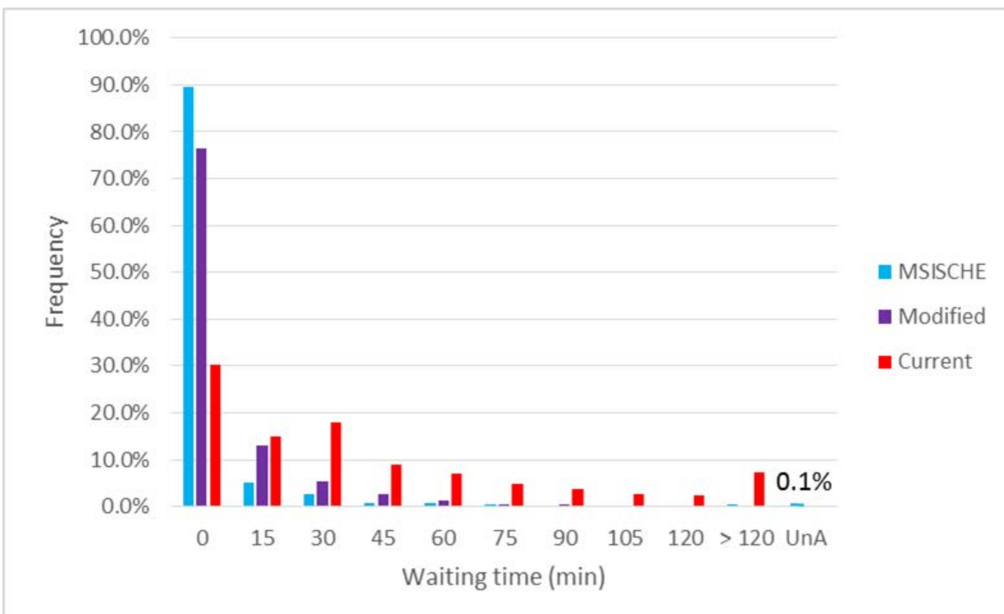


Figure 32. Number of Aircraft Waiting to Conduct Cold Refueling in 100 Scenarios When Adding a Squadron to the Original Setup



The far-right column represents the percentage of unassigned aircraft.

Figure 33. Frequency of Cold Refueling Wait Time over 100 Scenarios When Adding a Squadron to the Original Setup

These previous four figures show that the results of conducting cold refueling with the added squadron in general mirror those from conducting cold refueling with the baseline. On average, the values of maximum aircraft refueling wait time, average aircraft refueling wait time, and number of aircraft waiting for cold refueling, for those events scheduled by MSISCHE, improved by 62.7%, 91.2%, and 85.1%, respectively, when following MSISCHE in place of the current refueling policy.

About four percent of the 100 scenarios did not include every requested event in MSISCHE's optimal solution, resulting on 0.1% of requested sorties not being scheduled over all scenarios. Therefore, to keep a balanced solution, in which high peak demands do not supersede the available refueling resources, adding a squadron requires the addition of more refueling resources or decrease the number of flying events per squadron.

3. Adding Truck Breakdowns to the Original Setup

In order to conduct sensitivity analysis of having a truck breakdown, Generator randomly selected a truck to be out of service and in maintenance for a specific length of time. The times to start and finish maintenance are randomly chosen between 0000 to 0800 and 1800 to 2400, respectively by using a discrete uniform distribution of 15-minute increments. Only one truck can be in maintenance during a day, and it could refuel before going back to service.

Figures 34 through 37 present the comparisons, in regards to hot refueling wait time, among the three executions of Generator with the 100 scenarios produced while having a truck in maintenance. Figure 34 shows the difference in the maximum wait time that aircraft have to incur to conduct hot refueling. Figure 35 displays the comparison of the average aircraft wait time before hot refueling. Figure 36 illustrates the number of aircraft that waited to conduct hot refueling. Figure 37 compares the hot refueling wait time when aircraft follow the three alternatives of flight and refueling schedules. The UnA column represents the 0.1% of unassigned sorties in MSISCHE's solution. Referring to our previous statement in Section IV.C.2, unassigned sorties occur because refueling demand cannot be adequately smoothed using at most a two-hour schedule shift in either direction to avoid refueling delays. Figures 34 through 36 only display data pertaining to the aircraft that actually fly in each of the three executions (MSISCHE, modified refueling policy, and current refueling policy) and do not reflect the flights that are unassigned by MSISCHE.

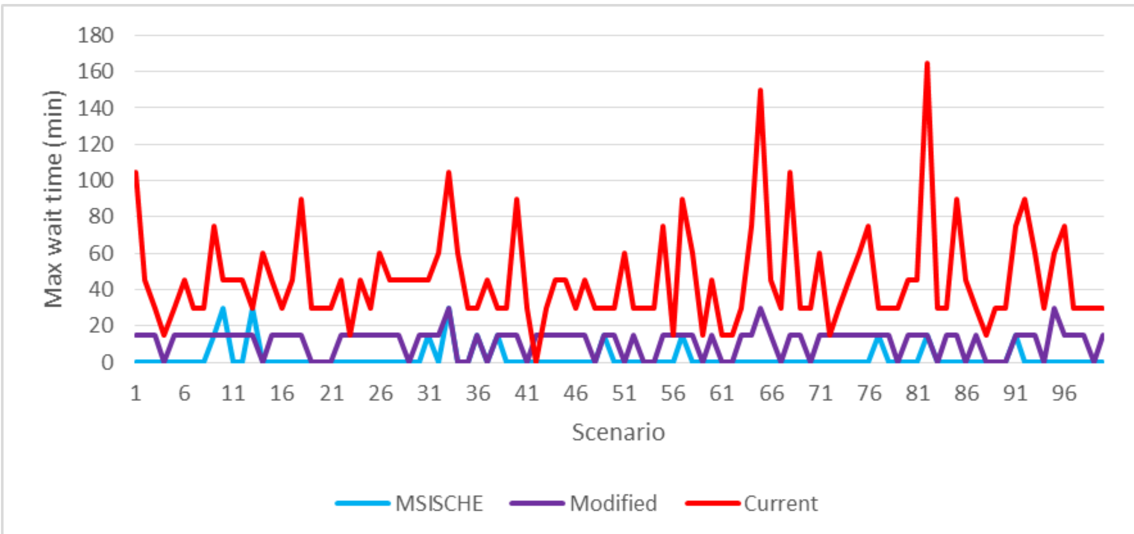


Figure 34. Maximum Wait Time to Conduct Hot Refueling in 100 Scenarios When Adding a Truck Breakdown to the Original Setup

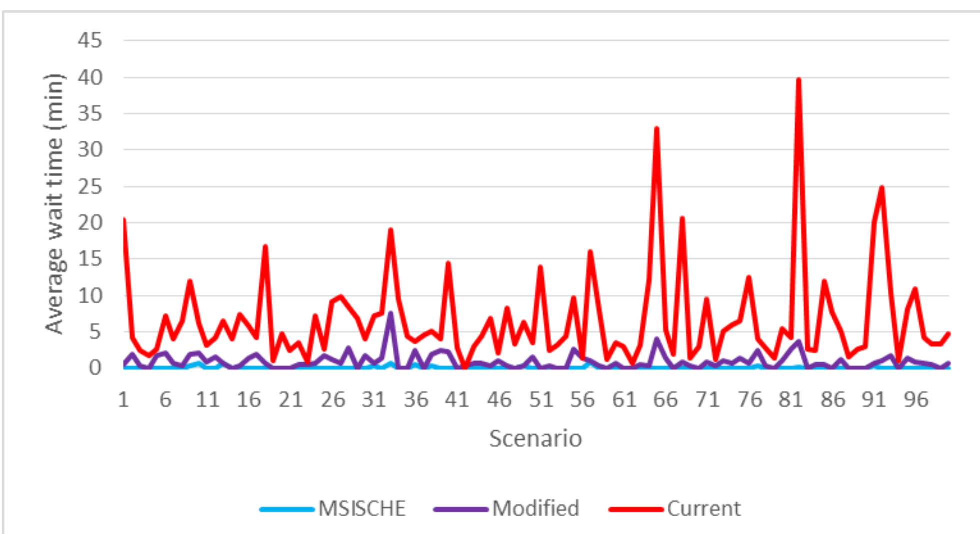


Figure 35. Average Wait Time to Conduct Hot Refueling in 100 Scenarios When Adding a Truck Breakdown to the Original Setup (Averaged over all Flights)

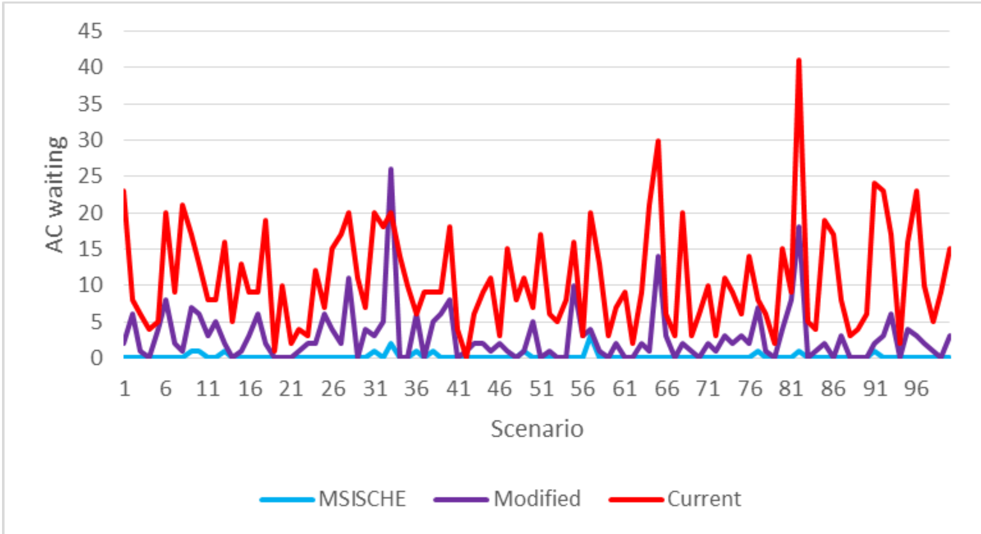
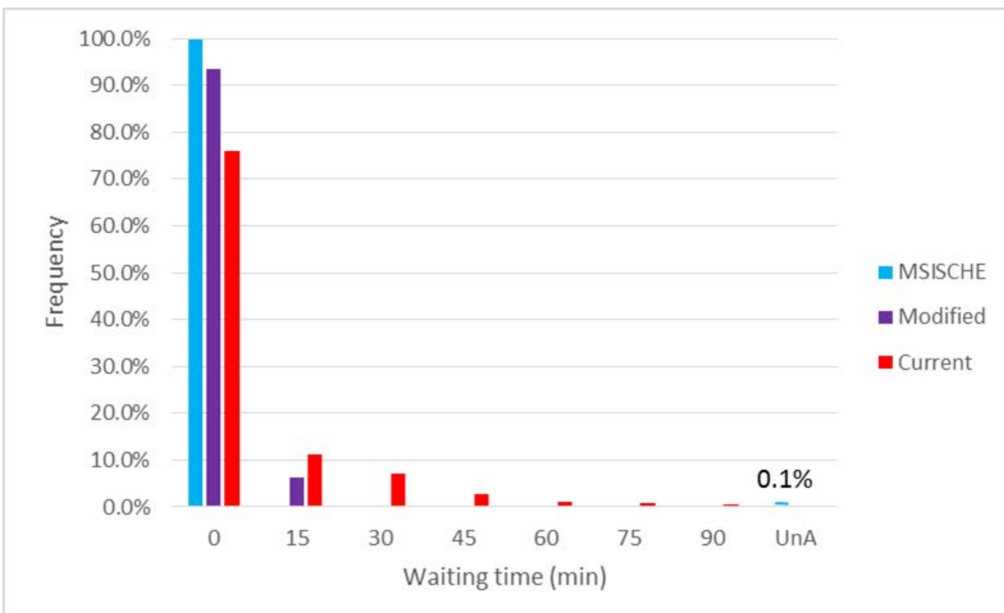


Figure 36. Number of Aircraft Waiting to Conduct Hot Refueling in 100 Scenarios When Adding a Truck Breakdown to the Original Setup



The far-right column represents the percentage of unassigned aircraft.

Figure 37. Frequency of Hot Refueling Wait Time Over 100 Scenarios When Adding a Truck Breakdown to the Original Setup

These previous four figures indicate that the results of conducting hot refueling while including a truck breakdown generally behave like those from conducting hot refueling with the baseline. On average, the value of average aircraft refueling wait time increased by 6% after including the truck breakdown; however, by using MSISCHE, this value is reduced by 99.2% for those events scheduled by MSISCHE. On average, the values of maximum aircraft refueling wait time and number of aircraft waiting for hot refueling, for those events scheduled by MSISCHE, improved by 95.1% and 98.6%, respectively, when following MSISCHE instead of the current refueling policy.

Similar results for cold refueling appear in Figures 38 through 41. Figure 38 shows the difference in the maximum wait time that aircraft have to incur to conduct cold refueling. Figure 39 displays the comparison of the average aircraft wait time before cold refueling. Figure 40 illustrates the number of aircraft that waited to conduct cold refueling. Figure 41 compares the cold refueling wait time when aircraft follow the three variants of flight and refueling schedules. The UnA column represents the 0.1% of unassigned sorties or aircraft not included in MSISCHE's solution. Figures 38 through 40 only display data pertaining to the aircraft that actually fly in each of the three executions (MSISCHE, modified refueling policy, and current refueling policy).

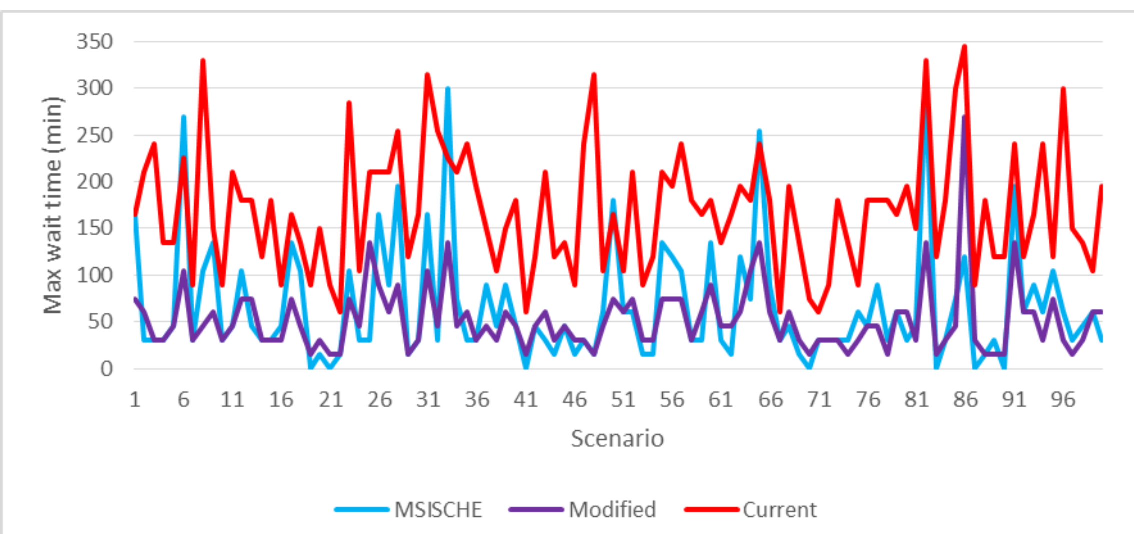


Figure 38. Maximum Wait Time to Conduct Cold Refueling in 100 Scenarios When Adding a Truck Breakdown to the Original Setup

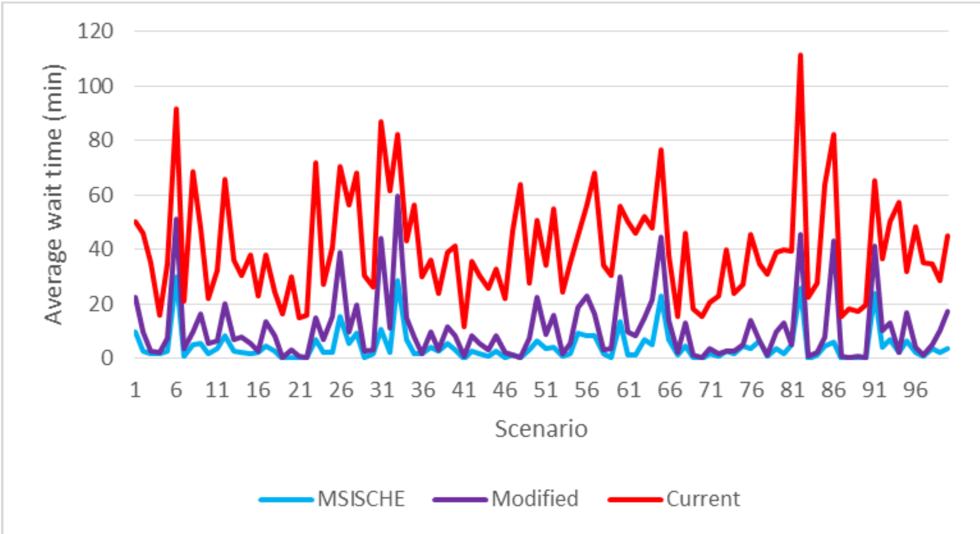


Figure 39. Average Wait Time to Conduct Cold Refueling in 100 Scenarios When Adding a Truck Breakdown to the Original Setup (Averaged over all Flights)

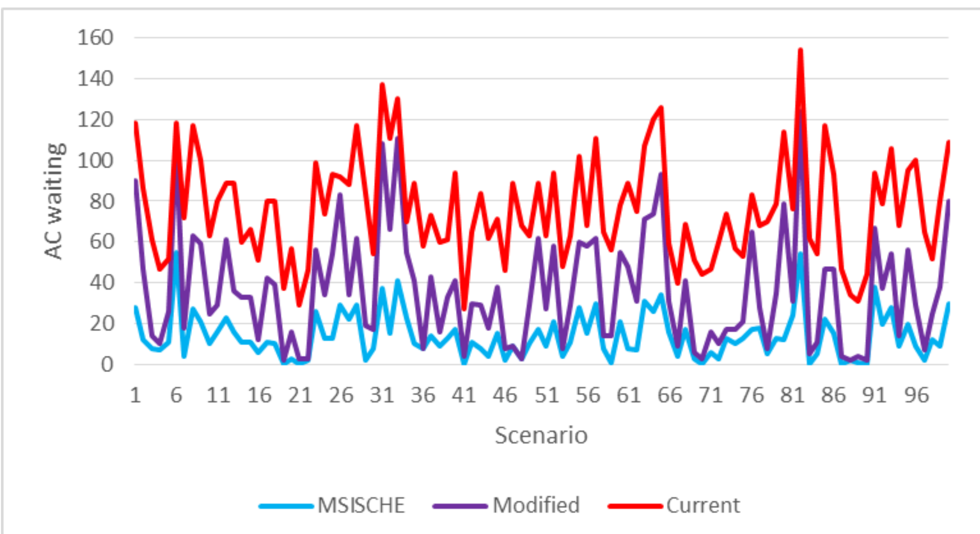
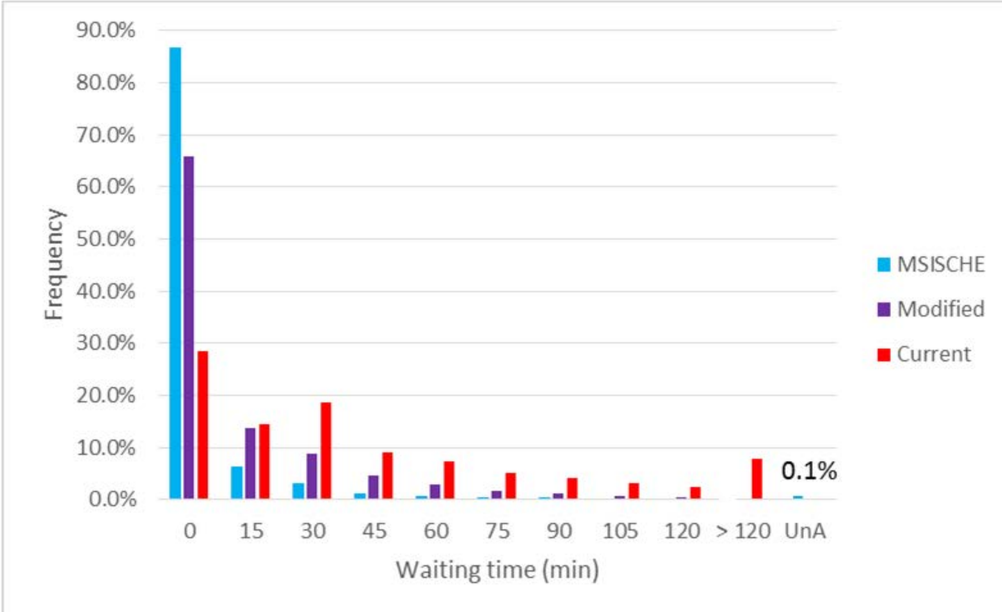


Figure 40. Number of Aircraft Waiting to Conduct Cold Refueling in 100 Scenarios When Adding a Truck Breakdown to the Original Setup



The far-right column represents the percentage of unassigned aircraft.

Figure 41. Frequency of Cold Refueling Wait Time over 100 Scenarios When Adding a Truck Breakdown to the Original Setup

These previous four figures show that the results of conducting cold refueling while including a truck breakdown in general behave like those from conducting cold refueling with the baseline. On average, the values of maximum aircraft refueling wait time, average aircraft refueling wait time, and number of aircraft waiting for cold refueling, for those events scheduled by MSISCHE, improved by 61.1%, 88.9%, and 81.6%, respectively, when following MSISCHE rather than the current refueling policy.

About three percent of the 100 scenarios did not include every requested event in MSISCHE's optimal solution, resulting in 0.1% of requested sorties not being scheduled over all scenarios. Therefore, we do not recommend to decrease the number of fuel trucks; in other words, a fuel truck must be replaced before it goes to maintenance. Otherwise, to keep a balanced solution, in which high peak demands do not supersede the available refueling resources, it will be necessary to decrease the number of flying events per squadron.

4. Including Reduction in Fuel Truck Driver Workforce to the Original Setup

Sensitivity analysis of reducing the fuel truck driver workforce by one driver was done by randomly selecting one of the four drivers' shifts that will have one fewer driver. Only one driver can be down in a day. Each of the 100 scenarios does its shift selection independently.

Figures 42 through 45 present the comparisons, in regards to hot refueling wait time, among the three executions of Generator with the 100 scenarios produced while having a reduction by one of the driver workforce. Figure 42 shows the difference in the maximum wait time that aircraft have to incur to conduct hot refueling. Figure 43 displays the comparison of the average aircraft wait time before hot refueling. Figure 44 illustrates the number of aircraft that waited to conduct hot refueling. Figure 45 compares the hot refueling wait time when aircraft follow the three alternatives of flight and refueling schedules while reducing the fuel truck driver workforce by one driver. The UnA column represents the 0.4% of unassigned sorties in MSISCHE's solution. As previously mentioned in Section IV.C.2, unassigned sorties occur because refueling demand cannot be adequately smoothed using at most a two-hour schedule shift in either direction to avoid refueling delays. Figures 42 through 44 only display data pertaining to the aircraft that actually fly in each of the three executions (MSISCHE, modified refueling policy, and current refueling policy) and do not reflect the flights that are unassigned by MSISCHE.

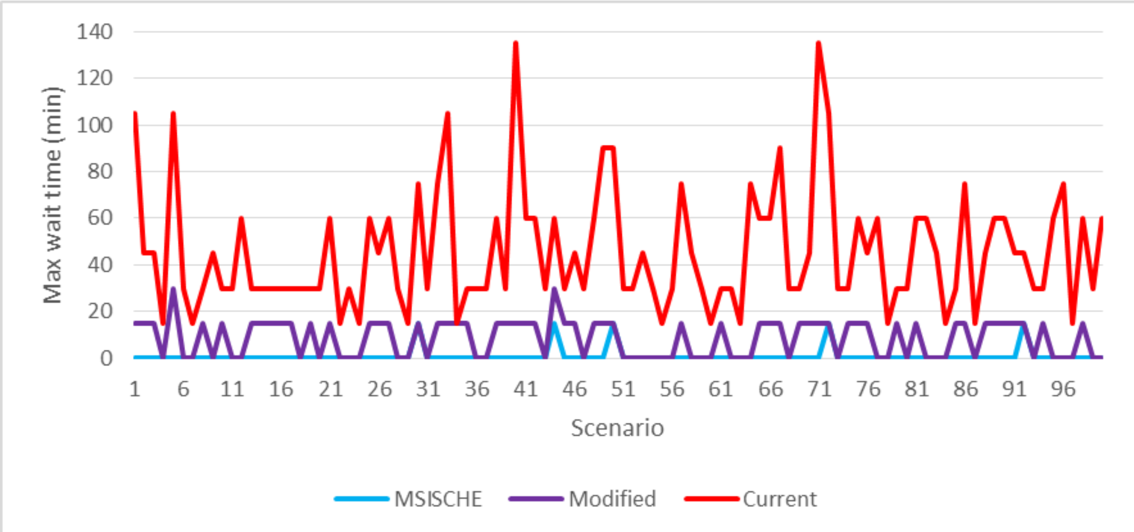


Figure 42. Maximum Wait Time to Conduct Hot Refueling in 100 Scenarios with One Fewer Driver from the Original Setup

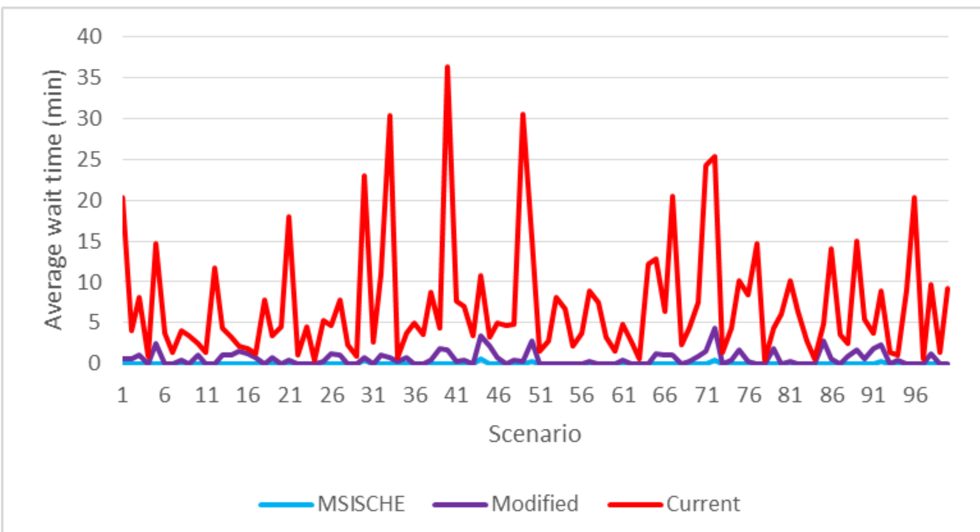


Figure 43. Average Wait Time to Conduct Hot Refueling in 100 Scenarios with One Fewer Driver from the Original Setup (Averaged over all Flights)

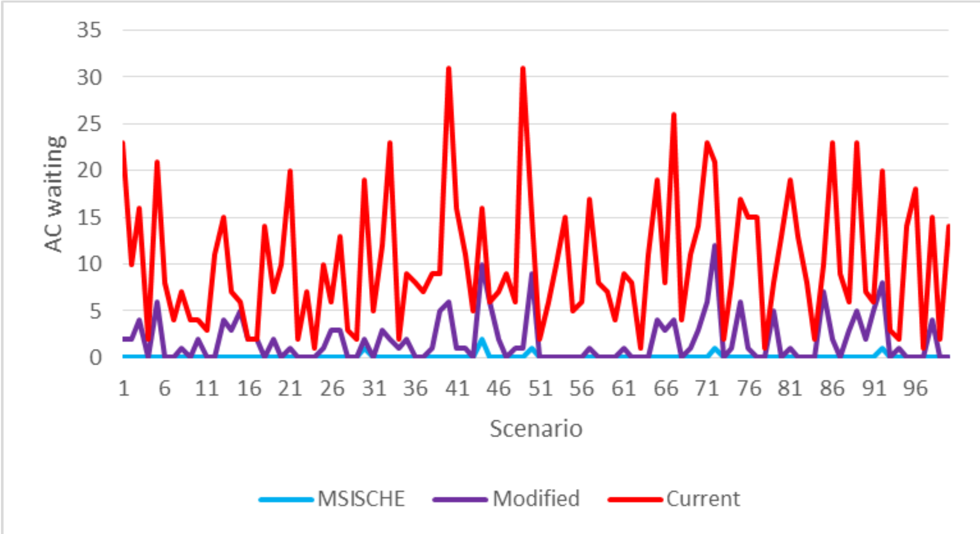
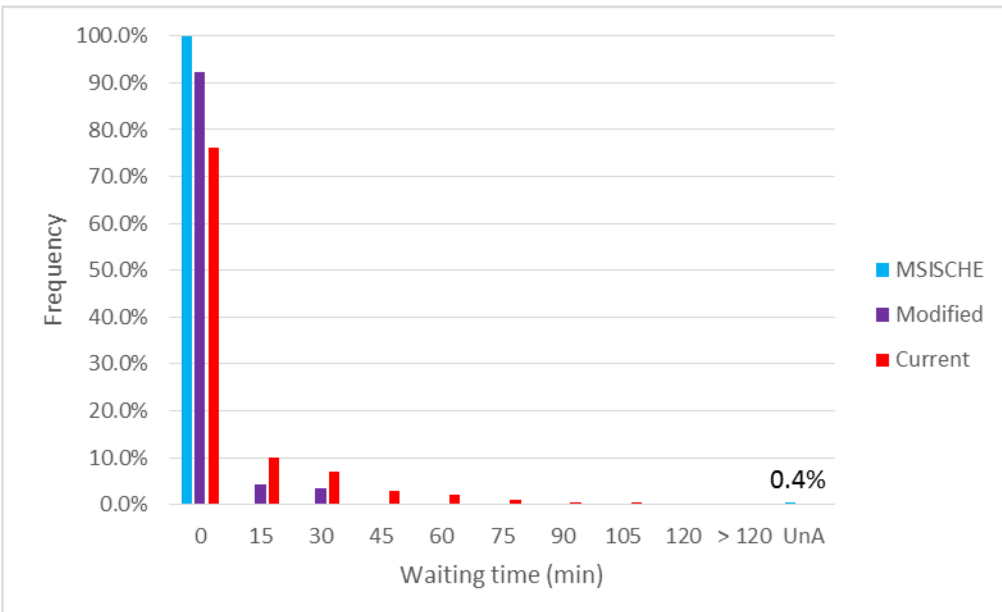


Figure 44. Number of Aircraft Waiting to Conduct Hot Refueling in 100 Scenarios with One Fewer Driver from the Original Setup



The far-right column represents the percentage of unassigned aircraft.

Figure 45. Frequency of Hot Refueling Wait Time over 100 Scenarios with One Fewer Driver from the Original Setup

These previous four figures indicate that the results of conducting hot refueling while including a reduction on the fuel truck driver workforce generally mirror those from conducting hot refueling with the baseline. On average, the value of average aircraft refueling wait time increased by 1% after including the workforce’s reduction; however, by using MSISCHE, this value is reduced by 99.7% for those events scheduled by MSISCHE. On average, the values of maximum aircraft refueling wait time and number of aircraft waiting for hot refueling, for those events scheduled by MSISCHE, improved by 98.4% and 99.4%, respectively, when following MSISCHE instead of the current refueling policy.

Similar results for cold refueling appear in Figures 46 through 49. Figure 46 shows the difference in the maximum wait time that aircraft have to incur to conduct cold refueling. Figure 47 displays the comparison of the average aircraft wait time before cold refueling. Figure 48 illustrates the number of aircraft that waited to conduct cold refueling. Figure 49 compares the cold refueling wait time when aircraft follow the three variants of flight and refueling schedules. The UnA column represents the 0.1% of unassigned sorties or aircraft not included in MSISCHE’s solution. Figures 46 through 48 only display data pertaining to the aircraft that actually fly in each of the three executions (MSISCHE, modified refueling policy, and current refueling policy).

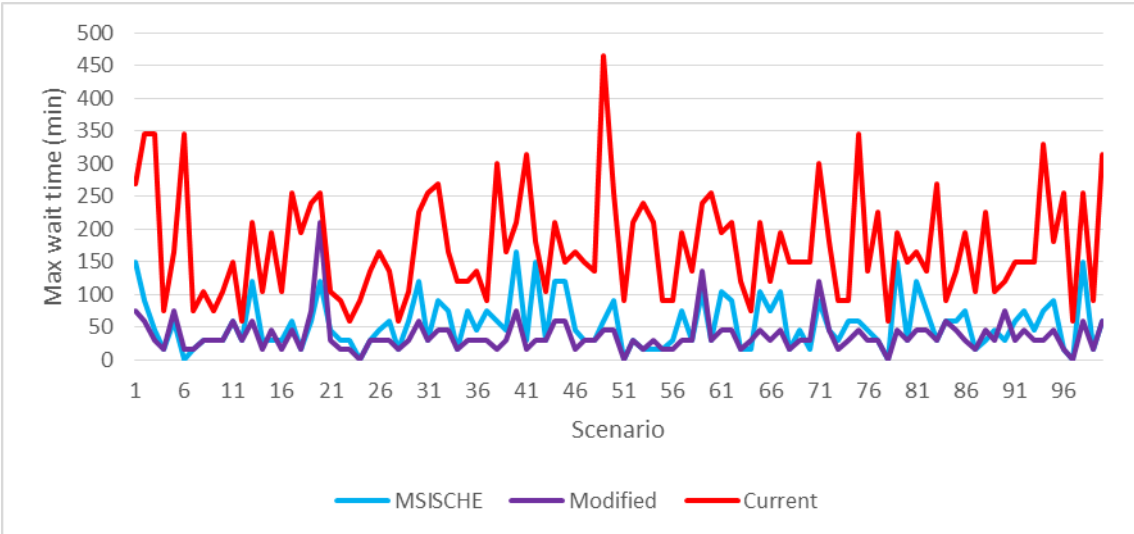


Figure 46. Maximum Wait Time to Conduct Cold Refueling in 100 Scenarios with One Fewer Driver from the Original Setup

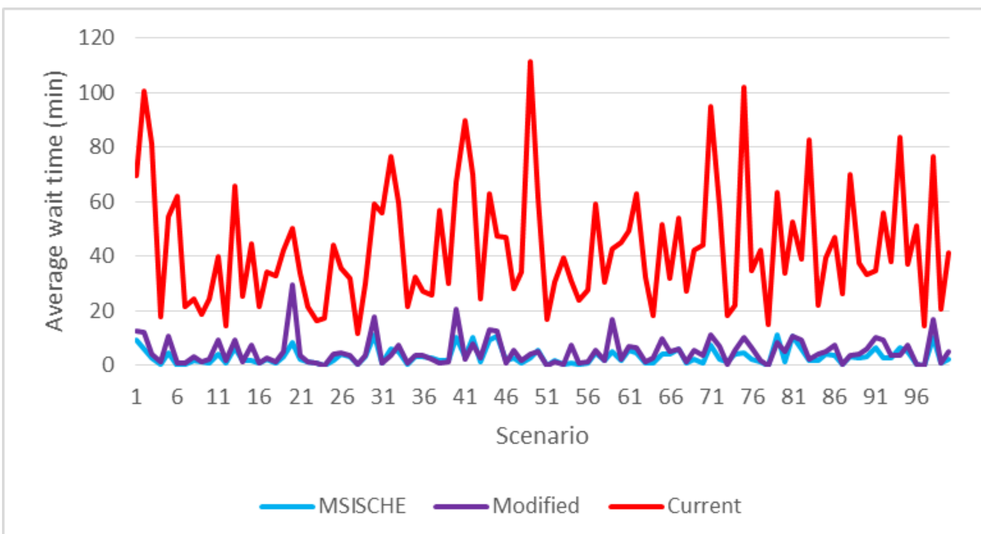


Figure 47. Average Wait Time to Conduct Cold Refueling in 100 Scenarios with One Fewer Driver from the Original Setup (Averaged over all Flights)

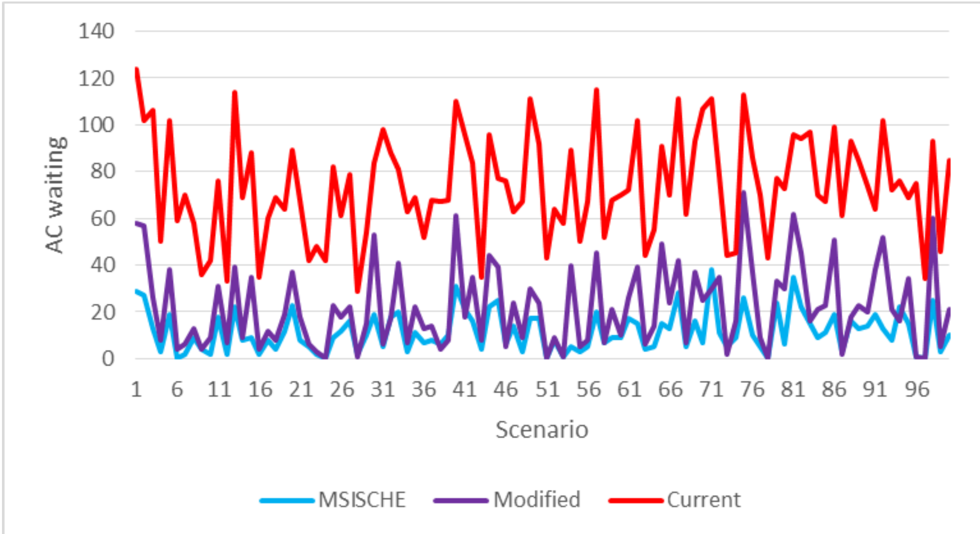
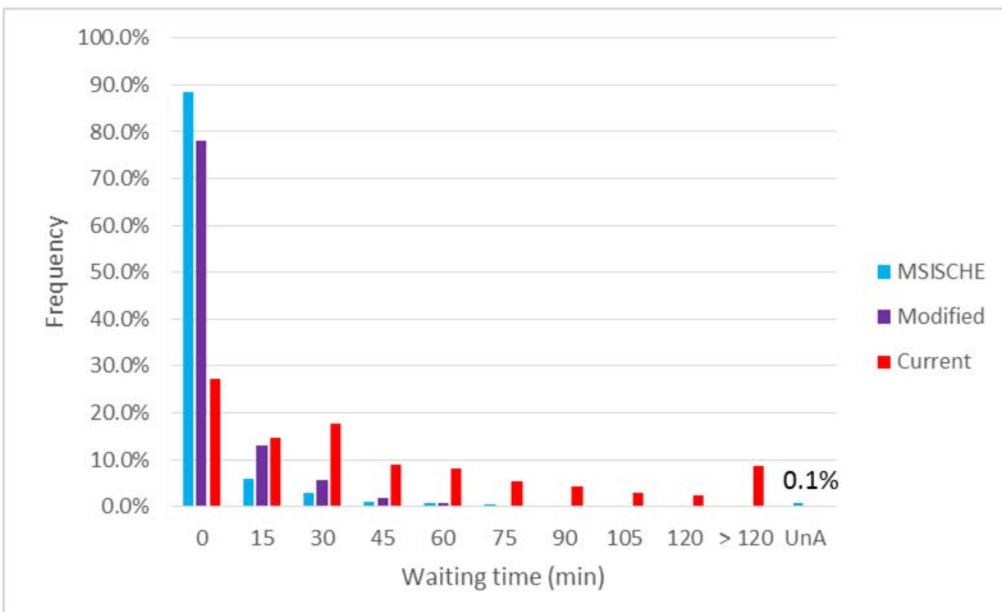


Figure 48. Number of Aircraft Waiting to Conduct Cold Refueling in 100 Scenarios with One Fewer Driver from the Original Setup



The far-right column represents the percentage of unassigned aircraft.

Figure 49. Frequency of Cold Refueling Wait Time Over 100 Scenarios with One Fewer Driver from the Original Setup

These previous four figures show that the results of conducting cold refueling while including a reduction on the fuel truck driver workforce in general mirror those from conducting cold refueling with the baseline. On average, the values of maximum aircraft refueling wait time, average aircraft refueling wait time, and number of aircraft waiting for cold refueling, for those events scheduled by MSISCHE, improved by 68.8%, 92.5%, and 84.2%, respectively, when following MSISCHE rather than the current refueling policy.

About six percent of the 100 scenarios did not include every requested event in MSISCHE's optimal solution, resulting on 0.2% of requested sorties not being scheduled over all scenarios. Therefore, we do not recommend decreasing the number of truck drivers. If a truck driver does not show for work and in order to keep a balanced solution, in which high peak demands do not supersede the available refueling resources, it might be necessary to decrease the number of flying events per squadron.

V. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

The most important finding in our study is that, with the current squadrons and refueling infrastructure at NAS Lemoore, it is possible to significantly reduce aircraft refueling wait time with only small adjustments to the squadrons' flight schedules; thus, the squadrons maintain their autonomy when creating their flight schedules and the aircraft increase their available flying time. MSISCHE has the ability to produce an optimized combined flying and refueling schedule, a balanced solution in which high peak demands do not supersede the available refueling resources. By using penalties and rewards, MSISCHE allows CSFWP and NAVSUP FLC San Diego to emphasize the priorities of the squadrons and their refueling service.

MSISCHE is fast and flexible, and can be adjusted if the refueling infrastructure changes. Nevertheless, if the refueling resources decrease or the number of squadrons increases, there is a possibility that some flying events will be unscheduled because MSISCHE does not allow aircraft to wait beyond two hours. In practice, flying events do get cancelled due to delays in refueling, and such cancellations would become more frequent as aircraft number increases or refueling infrastructure declines. NAS Lemoore leadership must carefully consider the cost of burning fuel while aircraft wait at hot skids and the balance between minimizing the aircraft refueling wait time and minimizing the changes to the squadrons' flight schedules when using MSISCHE or any scheduling tool.

Our findings also indicate that the aircraft refueling wait time can also be decreased simply by changing the refueling policy from only allowing aircraft to conduct hot refueling at the pre-assigned fuel skid to allowing aircraft to receive hot refueling at any fuel skid. Our simulation results indicate that this modification results in lower wait times than the current policy, but not as low as when aircraft follow MSISCHE's schedule.

B. FUTURE WORK

The following recommendations can improve MSISCHE's design and performance.

(1) Week-Prior Inputs

Because the squadrons' flight schedules are provided only a day prior to the flying date, the possibilities of modifying events are very low. To allow the possibility of modifying events of aircraft flying to additional MOA/ranges, we recommend providing the flight requests a week before the flying date.

(2) Hot Refueling Vehicle

Fuel trucks are currently used for both cold and hot refueling; however, for hot refueling, fuel trucks are used just as means of transportation for refueling personnel. Having another type of vehicle for hot refueling services could improve cold refueling wait time.

(3) Personnel Breaks

For simplicity, we do not model breaks during drivers' work shifts. To improve MSISCHE's accuracy, we recommend that breaks be modeled.

(4) Time Horizon

MSISCHE is a discrete-time model, and our study used 15-minute time increments in order to coincide with the squadrons' flight schedules as provided. In order to improve MSISCHE's accuracy while refueling aircraft, time increments could be shortened.

(5) Aircraft Assignment

Our study did not track individual aircraft in order to ensure that they have completed refueling prior to being assigned to additional events. Future work could add this level of fidelity.

(6) Compute Fuel

For simplicity, we assumed that the estimated fuel burned in an event is annotated in the flight schedule. If more information about the events is provided, the fuel burned for each event could be computed using the type of mission and duration of the flight.

(7) Include Aircraft Defueling

Along with aircraft refueling, NAS Lemoore Fuels Division also performs aircraft defueling. Fuel trucks are not an issue because, besides the 11 trucks used for refueling, another truck exists for defueling purposes; however, one of the available drivers will be occupied with that duty. We recommend taking aircraft defueling into consideration.

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LIST OF REFERENCES

Commander Strike Fighter Wing Pacific. (2016). *NAS Lemoore inflight guide*. Lemoore, CA: Author.

Defense Acquisition University. (2015). *Glossary of defense acquisition acronyms and terms.* Retrieved from https://dap.dau.mil/glossary/Pages/Default.aspx

GAMS. (2015). *General Algebraic Modeling System Development Corporation, version 24.4.2 r51415 (64 bit)*. Retrieved from https://www.gams.com

Geiser, M. T. (2012). *Improving aircraft refueling procedures at NAS Oceana* (Master's thesis). Retrieved from Calhoun http://calhoun.nps.edu/handle/10945/7346

Gerber, C. A. & Clark, J. A. (2013). *More fight–less fuel: Reducing fuel burn through ground process improvement* (Master's thesis). Retrieved from Calhoun http://calhoun.nps.edu/handle/10945/34667

Microsoft. (2009). *Microsoft Windows 7 Professional (64 bit)*. Retrieved from https://www.nps.edu/Technology/SoftwareLib

Microsoft. (2013). *Microsoft Office Professional Plus 2013: Microsoft Excel version 15.0.4885.1000 (64 bit)*. Retrieved from https://www.nps.edu/Technology/SoftwareLib

Naval Air Systems Command. (2002). *Aircraft refueling manual* (NAVAIR 00-80T-109). Washington, DC: Department of the Navy.

Ward, P. W. (2016). NAS Lemoore modeling project. Presented at OA4611 Joint Logistics Models, Naval Postgraduate School, Monterey, CA.

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