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THESIS

MILITARY FREE FALL SCHEDULING AND MANIFEST OPTIMIZATION MODEL

by

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December 2016

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MILITARY FREE FALL SCHEDULING AND MANIFEST OPTIMIZATION MODEL

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requirements for the degree of

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ABSTRACT

The United States Army Special Operations Command mandate to have all Green Berets be military free fall qualified essentially doubled the number of students in the course. This thesis uses an optimization tool for the manifest station to streamline airborne operations and reduce aircraft dwell time, thus saving money and enhancing use of resources. The military free fall scheduling and manifest optimization model is based on the existing scheduling dilemma model with original parameters. This model prescribes the number of jumpers per pass, depicts planned aircraft dwell time, and predicts duty day length. This information will help the command team make validated decisions regarding future class sizes and methods of training execution.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

ACT	aircraft cycle time
ASWORG	Antisubmarine Warfare Operations Research Group
BRAC	base realignment and closure
ERO	engine running on/off load
FAA	Federal Aviation Administration
HAHO	high altitude, high opening
HALO	high altitude, low opening
ICT	instructor cycle time
JAAT	joint airborne air transportability training
JMPI	jumpmaster prejump inspection
MAC-V SOG	Military Assistance Command–Vietnam, Studies and Observation Group
MFF	military free fall
MFFC	Military Free Fall Parachutist Course
ODA	operational detachment alpha
SCT	student cycle time
USAJFKSWCS	United States Army John Fitzgerald Kennedy Special Warfare Center and School
USASOC	United States Army Special Operations Command
YPG	Yuma Proving Ground

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EXECUTIVE SUMMARY

In 2012, the United States Special Operations Command released a “military free fall for all” concept requiring every Green Beret to be military free fall qualified. This concept essentially doubled the number of students in the Military Free Fall Parachutist Course (MFFC) from 560 in FY-12 to 1,200 in FY-16 (USAJFKSWCS 2015). A cost snapshot for the MFFC for FY-16 shows a total cost of $11.4M, about 85% of which is due to expansion (USAJFKSWCS 2015). According to Major Josh Enke, the commander of the MFFC, the biggest cost factor of the expansion project is “wasted blade time,” or the dwell time while aircraft sit on the tarmac with engines running waiting for the next student load.

The annual blade hour cost, which consists of fuel, maintenance, and personnel, is $5.6M for FY-16 (USAJFKSWCS 2015). Up to two hours each day are wasted on dwell time, with a cost of $4,500 per hour (J. Enke, personal communication, 2016). The most immediate concern therefore is reducing this dwell time.

In October 2015, Dr. Lee Ewing from the Operations Research Department at the Naval Postgraduate School went to Yuma Proving Ground (YPG) at the request of the commander of the MFFC. As a result of the site survey, it was recommended that the staff determine the best daily flight schedule and student manifest given existing or proposed resources. The resulting scheduling and manifest optimization tool, referred to as the “manifest model” hereafter, develops a manifest which efficiently uses aircraft and instructor resources and at the same time completes MFFC training objectives.

This thesis seeks to determine how the MFFC can manifest students to most efficiently use the assets available, minimizing or eliminating dwell time. This mixed-integer programming model uses parameters broken down into three components. The first component, student cycle time (SCT), is the total amount of time it takes a student to put on a parachute, jump, assemble, and move back to the personnel shed to begin the process all over again. The second component, aircraft cycle time (ACT), includes loading the aircraft at the personnel shed, taking off, climbing to jump altitude, releasing the student jumpers, flying back to the airfield, landing, and offloading any passengers. The final component is instructor cycle time (ICT), the total amount of time it takes the instructor to put on a parachute, jump, assemble, move back to the personnel shed, debrief a student, and get ready to start the process again.

When all of the data has been collected and the model implemented using a computer and relevant software, the manifest model produces a daily lift schedule for the MFFC. As previously mentioned, the purpose of this model is to minimize or eliminate dwell time while ensuring that the jump day is not extended past the authorized aircrew day by creating additional lifts. The authorized aircrew day is eight hours. Once the model is running optimally and provides a solution, the MFFC can implement the manifests. Analysis of the solutions provided by the model can inform the MFFC's future resource-allocation decisions.

The model also shows when dwell time occurs. Planned aircraft dwell time allows the other courses at YPG (the MFF Jumpmaster Course, Advanced Tactical Infiltration Course, MFF Instructor Course, and Rigger Course) to use the aircraft. This will increase efficiency for the other courses and allow each course to reduce time spent waiting for available aircraft. Finally, the model calculates how long the duty day will be.

Two specific scenarios, one based on a 60-student class using MC-4 parachutes and one based on an 80-student class using RA-1 parachutes, were run with varying results. Many of the findings from Scenario 1 are applicable to Scenario 2. In Scenario 1, the average planned dwell time per configuration was 28 minutes, whereas in Scenario 2 it was zero. The major difference between the scenarios is that students have two packed parachutes in Scenario 2, which eliminates dwell time. The average duty day increases 20 minutes from Scenario 1 to Scenario 2. We attribute this to increasing the total number of students in the class from 60 to 80.

This change was also a result of the model: The MFFC used the model output to validate a new course of action developed by MFFC staff for day-to-day operations to mitigate instructor fatigue. Originally, the MFFC offered 20 classes of 60 students each per year. Each class had two weeks of overlap, which included a week where two classes of students conducted jumps each day. The strain on the instructors led to multiple injuries to instructors. The MFFC proposed offering 15 classes of 80 students each per year. This proposal reduces the class overlap to one week with no jump overlap.

The value of the manifest model is the insights it provides the decision makers at the MFFC. Major Enke, the MFFC commander, states, “The model helped us look outside the constraints we were initially looking at. Dr. Ewing told us to ‘assume we would get more parachutes and space for the students. The biggest constraint is the use of aircraft. Focus on that.’ We didn’t see that the aircraft piece was the solution to maximizing student throughput” (J. Enke, personal communication, 2016).

The most important finding determines the optimal number of students per lift. Reducing the number of students to less than the maximum capacity of the aircraft facilitated minimal aircraft dwell time. The second scenario identifies no planned dwell time, which in theory will save the school thousands of dollars in wasted blade time per duty day. In addition to reducing operating costs, it also validates a new course of action developed by MFFC staff for day-to-day operations to mitigate instructor fatigue. The MFFC staff took the model output and used the product as left and right limits on how to get 80 students to jump a specified number of times per day (J. Enke, personal communication, 2016).

This analysis of the model’s results influenced the decision makers at the MFFC to determine the best way to run an 80-student class with the RA-1 parachute ahead of their original implementation deadline. The model provided left and right limits and then mathematical validation for the current course of action. Future versions of this model could be applied to other training courses experiencing scheduling dilemmas.

Reference

United States Army John Fitzgerald Kennedy Special Warfare Center and School. 2015. *Military Free Fall Expansion.* Fort Bragg, NC: USAJFKSWCS, July 31.

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I. INTRODUCTION

The Military Free Fall Parachutist Course was directed to more than double its student output from 560 in FY12 to 1,200 in FY16 (USAJFKSWCS 2015). This was due to a “military free fall for all” concept from the commander of United States Special Operations Command in 2012 which requires every Green Beret to be military free fall qualified. The dramatic increase in students with minimal additional asset allocation has put serious strain on the instructors and equipment at the Military Free Fall Parachutist Course. One of the places this strain is most visible is at student manifest, which is where the daily jump schedule is created. Currently the school is attempting to streamline the manifest process through trial-and-error techniques. By using an integer linear programming formulation, we used a manifest-optimization tool that prescribes the number of jumpers to put on the plane for each lift. The tool will write manifests that will allow the school to efficiently use all available resources.

This study provides background in parachuting operations and the Military Free Fall Parachutist Course. The literature review describes operations research and relevant scheduling techniques. Following the literature review, we describe our methodology. The model output data is analyzed and applied to the course. Finally, we discuss the implications of the manifest tool for the course as well as for other potential Special Operations Forces course optimization problems.

A. MILITARY FREE FALL BACKGROUND

Unlike static line parachuting, where the jumper’s parachute is deployed for him, military free fall (MFF) jumpers deploy their own parachutes. There are two types of MFF operations defined in the FM 3-05.211, *Special Forces Military Free-Fall Operations*:

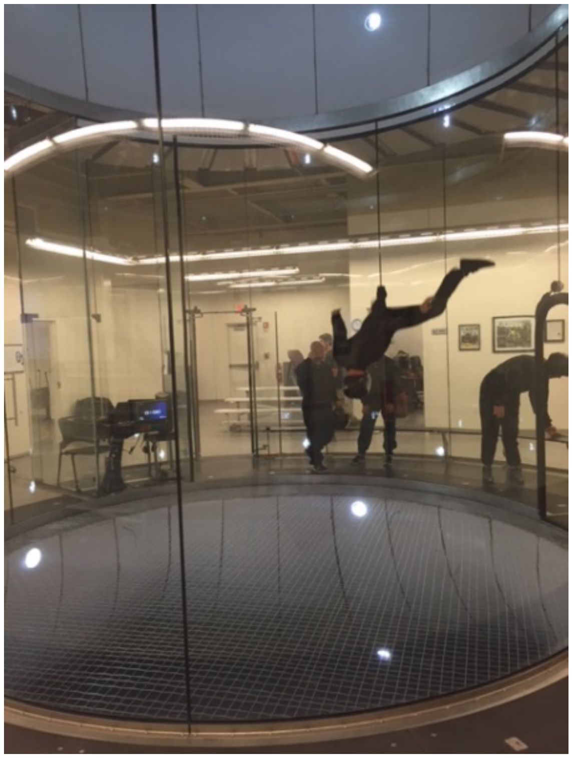
> High-Altitude Low-Opening (HALO) is a jump made with an exit altitude of up to 35,000 feet mean sea level and a parachute deployment altitude at or below 6,000 feet above ground level. HALO infiltrations are the preferred MFF method of infiltration when the enemy air defense posture is not a viable threat to the infiltration platform. HALO infiltrations

> require the infiltration platform to fly within several kilometers of the drop zone.
>
> High-Altitude High-Opening (HAHO) operations are standoff infiltration jumps made with an exit altitude of up to 35,000 feet above mean sea level and a parachute deployment altitude at or above 6,000 feet above ground level. HAHO infiltrations are the preferred method of infiltration when the enemy air defense threat is viable or when a low-signature infiltration is required. Standoff HAHO infiltrations provide commanders a means to drop MFF parachutists outside the air defense umbrella, where they can navigate undetected to the drop zone or objective area. (Department of the Army, 2005)

Many MFF insertions are conducted in a manner that is non-releasable to the public. One releasable MFF insertion in recent memory was January 1991 in support of Operation Desert Storm; the next was not until 2007, when Operational Detachment Alpha (ODA) 074 conducted an MFF insertion in Iraq (Owen 2008). ODA 074's mission did not result in the target being captured, but it did set a precedent that, with proper training and certification, military free fall is a viable insertion method. In 2012, Navy SEALs successfully conducted an MFF operation into Somalia to rescue American aid worker Jessica Buchanan and Danish aid worker Poul Thisted (Mazzetti et al. 2015). More recently, in May 2016, the author attended a training exercise in Poland being conducted by the Polish GROM. Once the targeted individual had been identified, the assault team used MFF as their insertion method to interdict him. Special operations forces around the world are using MFF to accomplish tough missions in non-permissive environments. Military historian John Weeks says, "For inserting small bodies of raiders … there are some circumstances in which the free-fall drop has no equal" (Weeks 1976, 180).

The Military Free Fall Parachutist Course, which is the focus of this study, trains students to be military free fall parachutists. The course is four weeks long, and students typically jump 17–30 times. Prior to jumping at the MFFC, students spend a week learning how to pack the MC-4 main parachute, how to properly wear the parachute system, aircraft procedures, and emergency procedures. Students also "learn to fly" by practicing maintaining body position while flying in a vertical wind tunnel, located at Yuma Proving Ground (YPG) in southern Arizona (see Figure 1).

Figure 1. Military Free Fall Instructor Demonstrating the Vertical Wind Tunnel



An MFF instructor demonstrates a flying technique inside the vertical wind tunnel at YPG. Students reach a basic level of flying proficiency in the wind tunnel before jumping out of an airplane.

Once the students have demonstrated proficiency in these tasks, they move on to actual parachute operations. Jump progression begins with students jumping out of the plane with no equipment other than the parachute in order to master the proper aircraft exit procedures, actions in the air, deploying the parachute, and landing safely. After a graded exercise, students progress to jumping with combat equipment and wearing oxygen masks. The students must pass another graded exercise wearing the combat equipment and oxygen masks to move to the final block of instruction, which consists of HAHO jumps, also known as standoff jumps. Some HAHO operations are at night and require the student to wear combat equipment, oxygen, body armor, night-vision goggles, and intrateam radios. Once the student has successfully passed each graded exercise, he or she is a certified military free fall parachutist.

MFF operations can be traced back to World War II, to German officer Friedrich August Freiherr von der Heydte (Sutherland 1990, 168). He conducted various parachute experiments with the Fallschirmjäger Regiment 3 (Third Parachute Regiment) of the Luftwaffe First Airborne Division in Germany and later in Southern France. The techniques were refined and eventually brought to the United States. In the late 1950s, a select cadre from the 77th Special Forces Group was trained (Sutherland 1990). In 1962, the Advanced Training Committee was established at Fort Bragg, and they institutionalized MFF training (Hauck 2002, 146). As operational requirements increased in Southeast Asia, training courses were also established in Okinawa, Japan, by the First Special Forces Group and the Military Assistance Command–Vietnam, Studies and Observation Group (MAC-V SOG). The SOG veterans took lessons learned from operational jumps during the Vietnam War and applied them to a course, aiming to enhance free fall training and to build capacity.

According to Jose Reyes, the Chief Instructor at the MFFC, the first official Army Training Requirements and Resources System (ATTRS) military free fall course was in June of 1973 at Smoke Bomb Hill in Fort Bragg, North Carolina (J. Reyes, personal communication, 2016). The 18 students jumped approximately 16–18 times per class. The first 29 military free fall instructor certifications were issued to Vietnam veterans from MAC-V SOG and the Fifth and Seventh Special Forces Groups. The course utilized the Rhine Luzon Drop Zone at Camp Mackall, located 45 minutes west of Fort Bragg. Jumpers would load aircraft on the dirt airstrip in the center of the drop zone. As interest in qualifying more personnel increased, the course expanded. By the mid-1990s, Reyes explains, a new location was required to better facilitate the training.

The search for the ideal location took some time. In January of 1995, the course moved to the Naval Air Facility in El Centro, California. Three courses were conducted while a more permanent location could be found. El Centro wasn’t feasible for the long term as there were power lines running through the drop zone, it took 45 minutes to drive from the drop zone to the base, and air space was severely restricted (J. Reyes, personal communication, 2016). In June the same year, the course relocated to Yuma Proving Ground (YPG), Arizona. The U.S. Army Parachute Team (the Golden Knights) trained there during the winter, Reyes explains, so a footprint was already established for the course to settle into. YPG had a designated drop zone free of obstacles, an airfield in close proximity to the drop zone, and unlimited air space. According to Reyes, since YPG was one of the bases threatened with closure under Base Realignment and Closure (BRAC), the facility embraced the new tenant and facilitated the school's transition to the new location. The weather is also conducive to free fall operations, with approximately 320 jumpable days per year (J. Reyes, personal communication, 2016).

Hundreds of Department of Defense personnel have been trained there each year since 1995, and the school offers several other courses in addition to the basic parachutist course. In an informational brief given by Major Enke, all of the courses offered by the Military Free Fall School are described. The Military Free Fall Jumpmaster Course trains free-fall-qualified personnel to inspect jump equipment, plan and execute jumps, and safely put jumpers out of an aircraft. The Military Free Fall Instructor Course certifies free-fall-qualified personnel to train students in the tactic of military free fall. There they learn how to ensure students have a safe jump and how to rescue students from dangerous situations. The Advanced Tactical Infiltration Course trains individuals or free-fall-specialty ODAs in advanced MFF skills such as advanced night standoffs, bundle drops, and navigation techniques. The program of instruction certifies ODAs as "Level One qualified," a requirement to conduct MFF operations in combat. Lastly, the Special Operations Forces Rigger Course focuses on nonstandard equipment rigging, bundle release-point computations, advanced rigging techniques and procedures, and parachutist navigational-systems training (Enke 2015). While each of these courses has a wide range of requirements, the Military Free Fall Parachutist Course is the most demanding.

In August 2011, Major General Bennet Sacolick, the commanding general of the United States Army John Fitzgerald Kennedy Special Warfare Center and School (USAJFKSWCS), tasked his subordinate units to develop a course of action to qualify every Green Beret in military free fall. Once he received the plan, he briefed Lieutenant General John Mullholland, the commander of United States Special Operations Command (USASOC) on the Military Free Fall, in the concept. Mullholland deferred the decision to his successor, Lieutenant General Charles Cleveland, who quickly approved the concept in August 2012. Since then, the onus has been on USAJFKSWCS and the MFFC to handle the increased student throughput requirement.

From 1995–2013, there were 10 classes per year, training 45–52 students per class. From 2013–2015, the model consisted of 14 classes of 52 students each year for a total of 728 students trained annually, and the instructor to student ratio was 1:2 (J. Reyes, personal communication, 2016). The current model, according to Reyes, consists of 20 classes of 60 students a year for a total of 1,200 students trained annually, with a current instructor to student ratio of 1:3. This doubling of student throughput is a result of the “military free fall for all” mandate.

Several modifications have been made to the course to accommodate the increased student throughput. The training group hired contract parachute packers to pack instructor chutes. This has increased instructor time with students and helps reduce aircraft wait time for the next student load by 25% (USAJFKSWCS 2015). Phillips Drop Zone, the drop zone used for free fall operations in YPG, has also been expanded to facilitate more jumpers per pass. By eliminating the need for the aircraft to fly around waiting until it is safe to drop additional jumpers, an estimated two hours of flying time per day are saved (USAJFKSWCS 2015). In 2013, Admiral William McRaven, commander of United States Special Operations Command, approved seven C-27 aircraft to replace CASAs in USASOC. However, most of the aircraft are tasked across the entire command, not just at the MFFC. While the program as a whole gained three of the aircraft, only two are dedicated to the basic course (USAJFKSWCS 2015). This thesis explores the most efficient use of these and other aircraft available to MFFC.

A cost snapshot for the MFFC for FY-16 shows a total cost of $11.4M, about 83% of which is due to the expansion concept (USAJFKSWCS 2015). According to Major Josh Enke, the commander of the Military Free Fall Parachutist Course, the biggest cost detriment to the expansion project is “wasted blade time,” or the dwell time an aircraft incurs sitting on the tarmac with engines running waiting for the next student load (J. Enke, personal communication, 2016). The annual blade hour cost, which consists of fuel, maintenance, and personnel, is $5.6M for FY-16 (USAJFKSWCS 2015). Up to two hours each day are wasted on dwell time, with a cost of $4,500 per hour (J.

Enke, personal communication, 2016). The most immediate concern is reducing the amount of time that aircraft sit on the runway waiting for students to be ready, i.e., aircraft dwell time.

In October 2015, Dr. Lee Ewing from the Operations Research Department at the Naval Postgraduate School went to YPG at the request of the commander of the MFFC. When Dr. Ewing arrived, the MFFC staff was working on increasing student billeting, expanding the drop zone, and war-gaming class sizes. As a result of the site survey, it was recommended that the staff needed to determine the best daily flight schedule and student manifest given existing or proposed resources and that only after that should secondary questions be addressed by the MFFC command. The resulting scheduling and manifest-optimization tool, referred to as the "manifest model" going forward and presented in Chapter III, develops a manifest which efficiently uses aircraft and instructor resources and at the same time completes MFFC training objectives.

B. RESEARCH QUESTION AND PURPOSE

This thesis seeks to answer the following question: How can the Military Free Fall Parachutist Course manifest students to most efficiently use the assets available?

In doing so, the thesis will optimize manifests for students by minimizing or eliminating the amount of time an aircraft sits on the runway waiting for students. My analysis of the optimization model's results has been used by the MFFC to influence decisions regarding left and right limits for course sizes and execution. This model validates the course of action the MFFC is currently pursuing. The specifics will be discussed in Chapter V.

C. APPROACH

We used a model to solve this scheduling problem. Only some of the variables are required to have integer values, making it a mixed-integer programming model (Hillier and Lieberman 2010, 464). The primary parameters—the data—used to run the manifest-optimization model are presented as three components. The first component, student cycle time (SCT), is the total amount of time it takes a student to put on a parachute, jump, assemble, and move back to the personnel shed to begin the process all over again. The second component, aircraft cycle time (ACT), includes loading the aircraft at the personnel shed, taking off, climbing to jump altitude, releasing the student jumpers, flying back to the airfield, landing, and offloading any passengers. The final component is instructor cycle time (ICT), the total amount of time it takes the instructor to put on a parachute, jump, assemble, move back to the personnel shed, debrief a student, and get ready to start the process again. The parameters for the manifest model will be discussed at length in Chapter IV.

When all of this data is collected and the model is implemented using a computer and relevant software, the manifest model produces a daily lift schedule for the MFFC. As previously mentioned, the purpose of this model is to minimize or eliminate the amount of time the aircraft spend sitting on the runway waiting for students while ensuring that the jump day is not extended past the authorized aircrew day by creating additional lifts. The authorized aircrew day is eight hours. Once the model is running optimally and provides a solution, the MFFC implements the manifests. The resulting analysis of the optimal solutions provided by the model will be used to inform the MFFC's future resource-allocation decisions.

The model also shows the occasions when dwell time occurs. Scheduled aircraft dwell time can allow the other courses at YPG (the MFF Jumpmaster Course, Advanced Tactical Infiltration Course, MFF Instructor Course, and Rigger Course) to use the aircraft. This will increase the output for the other courses and allow each course to reduce time waiting for aircraft. Finally, the model calculates how long the duty day will be.

The next chapter will provide a brief background on operational research. Then, Chapter III will describe the optimization formulation. Chapter IV will describe the parameters used to populate the model, then it will discuss the model results and analysis.

II. LITERATURE REVIEW

This discussion will incorporate a brief background of operational research. Following the background, fundamentals of solving problems using operational research techniques are discussed. Finally, several examples of historical scheduling-optimization problems are outlined, providing a foundation for our manifest-optimization tool.

A. BACKGROUND

Optimization is one of the tools used by an operations researcher to help organizations make better decisions. As defined by Hillier and Lieberman, operations research is essentially "research on operations" and is "applied to problems that concern how to conduct and coordinate the operations within an organization" (Hillier and Lieberman 2010, 2). The terms *operations research* and *management science* are often used synonymously. Ragsdale defines management science as "a field of study that uses computers, statistics, and mathematics to solve business problems" (Ragsdale 2008, 1). Regardless of which term one uses, the science can be traced back to the mid-1500s to Girolamo Cardano, a Milanese physician, mathematician, and gambler (Gass and Assad 2005, 1). In his book *Liber de Ludo Aleae*, Cardano computes chance as the "ratio between the number of favorable outcomes and the total number of outcomes, assuming outcomes are equally likely" (Gass and Assad 2005, 1). Out of this historical foundation, operations research developed into its modern form and application during the WWII years.

In 1941, the United States faced a logistics issue transporting supplies across the Atlantic to Britain. Frank Hitchcock declared the trouble a "classical transportation problem," defined as "the shipping of goods from supply origins to demand destinations at minimal cost" (Gass and Assad 2005, 51). Economist Tjalling Koopmans found a solution while working for the British-American Combined Shipping Board, and the problem is now known as the Hitchcock-Koopmans transportation problem (Gass and Assad 2005, 51). The stage was set for operations research in the war effort.

Physicist Philip M. Morse developed the Antisubmarine Warfare Operations Research Group (ASWORG) with 15 civilian scientists for the U.S. Navy in 1942 (Gass and Assad, 52). One of their first successful tasks was to determine optimal search and convoy-escort patterns for allied shipping-patrol aircraft (Budiansky 2013, 191). Their most famous positive result came when the organization suggested changing the depth at which air-delivered depth bombs would detonate from 75 to 25 feet (Budiansky 2013, 191). Gass and Assad note the ASWORG also developed a "probabilistic-based approach to the optimal allocation of search effort" (Gass and Assad 2005, 54). Due to the organization's overwhelming success, by the end of the war, the ASWORG had morphed into the Operations Research Group and had almost 100 scientists working there (Gass and Assad 2005, 52).

The civilian sector retained the lessons learned during the war. After the armistice, a number of the operations research teams transitioned to the private sector. Many advancements in the science occurred during this time period. The simplex method, an algorithm for solving linear programming models, was developed by George Dantzig in 1947 (Hillier and Lieberman 2010, 2). As technology advanced, particularly computer technologies, operations research grew. Electronic computers facilitated arithmetic calculations millions of times faster than a human could conduct them. As early computers progressed to powerful personal systems, operations research technology became more accessible. Today, thousands of individuals are able to routinely solve operations research problems, most often in the fields of business analytics and big data.

While the operations researcher has many tools at his disposal, two techniques appear relevant to the MFFC manifest problem: simulation and mathematical optimization. While both are used to enhance decision making, they have mutually exclusive strengths and weaknesses. Optimization is often referred to as mathematical programming (Ragsdale 2008, 17). Simply put, optimization prescribes solutions that achieve pre-specified objectives while satisfying identified restrictions. On the other hand, Ragsdale defines simulation as "measures and describes various characteristics of the bottom-line performance measure of a model when one or more values for the independent variables are uncertain" (Ragsdale 2008, 572). Simulation on its own only describes the phenomena in question and cannot be used to prescribe the best set of solutions without explicit enumeration of all inputs. This study uses an optimization model because we wanted to prescribe a solution—the number of student jumpers to assign to each aircraft lift.

B. SCHEDULING-OPTIMIZATION PROBLEMS

Scheduling problems often have multiple parts, each with specific complexities and considerations, and are typically very difficult to solve. As previously mentioned, no documented operations research studies have addressed the MFFC manifest problem specifically. However, there are numerous examples of other successful scheduling-optimization models. The following examples showcase the wide range of scheduling-optimization application.

> In the United States, the Federal Aviation Administration (FAA) is responsible for providing air traffic management services and frequently faces situations where a large-scale weather system reduces airspace capacity. In June 2006, the FAA began using a tool known as Airspace Flow Programs that gave the FAA the ability to control activity in congested airspaces by issuing ground delays customized for each individual flight when large-scale thunderstorms block major flight routes. **Benefits:** During its first two years of use, the system saved aircraft operators an estimated $190 million. (Ragsdale 208, 2)

> In 2006, Netherlands Railways introduced a new timetable designed to support the growth of passenger and freight transport on a highly used railway network and to reduce the number of train delays. Constructing a railway timetable from scratch for about 5,500 daily trains is a complex challenge. To meet this challenge, techniques were used to generate several timetables, one of which was finally selected and implemented. Additionally, because rolling stock and crew costs are the most significant expenses for a railway operator, OR tools were used to design efficient schedules for these two resources. **Benefits:** The more efficient resource schedules and the increased number of passengers have increased annual profit by 40 million euros (US $60 million). Moreover, the trains are transporting more passengers on the same railway infrastructure with more on-time arrivals than ever before. (Ragsdale 208, 2)

> Since 2005, the Chilean Professional Soccer Association has used operations research techniques to schedule professional leagues in Chile. These techniques have yielded a direct economic impact of more than $55 million through a combination of increased ticket sales, cost savings, and

> subscriber growth for Chile's soccer television channel and cost reductions for the teams due to better travel schedules resulting from an improved ordering of home and away games. The same techniques have been used to schedule the South American 2018 FIFA World Cup qualifiers. This organization is a finalist for the prestigious 2016 Franz Edelman Award, which recognizes excellence in developing and applying analytical methods transforming real-world industries. (INFORMS 2015)

These are just a few scheduling-optimization models among dozens. This thesis will apply existing techniques from successful models to a new model and then apply that model to the MFFC. The next two chapters will discuss our manifest-optimization model in depth.

III. OPTIMIZATION FORMULATION

This chapter introduces our manifest-optimization model formulation. We will list the components of the model, explain its functionality, and describe the constraints in detail. Finally, we discuss model variations.

A. MODEL PARAMETERS

Introduced here are the student cycle time (SCT), aircraft cycle time (ACT), instructor cycle time (ICT) and the engine running on/off load (ERO) parameters with a more detailed discussion of the data associated with these parameters in Chapter IV. The remaining parameters are discussed in the next section.

Student cycle time is the total amount of time it takes a student to put on a parachute, jump, assemble, and move back to the personnel shed to begin the process all over again. Another primary model parameter, aircraft cycle time, includes loading the aircraft at the personnel shed, taking off and climbing to jump altitude, releasing the student jumpers, the flight back to the airfield and landing, and finishes with the offload of any air land passengers. Similar to the student cycle time, the instructor cycle time is the total amount of time it takes the instructor to don a parachute, jump, assemble, move back to the personnel shed, debrief a student, and get ready to start the process again. During passenger loading and offloading the aircraft conducts an engine running on-load/offload, or ERO, i.e., the plane does not shut down its engines while loading or unloading passengers.

B. FORMULATION

This formulation precisely describes the manifest optimization model developed by Dr. Ewing at the Naval Postgraduate School in Monterey, California in the fall of 2015. The objective function and constraint equations are discussed following the algebraic formulation.

1. Indices

l	lift (five-minute time increments)
s	student jumpers
i	instructor jumpers
a	aircraft
jmp	student jumper cycle, e.g., if jumper is on jump two for the day then *jmp*=2
k, j	aliases for lift l
jjmp	aliases for student jumper cycle *jmp*

Sets

$l \in L$	where L is the set of lifts available for a training day
$jmp \in J$	where J is the set of jumps for a training day

2. Parameters [Units of Measure]

sct_{jmp}	student cycle time for students on jump number *jmp* [five minutes/lift increment]
act_a	aircraft cycle time for aircraft a [five minutes/increment]
$fuel_a$	amount of time required for aircraft a to break for fuel [five minutes/lift increment]
ero_a	when aircraft a is available for ERO [five minutes/lift increment]
$w1_l$	weight factor increases by one for each lift increment
$w2_l$	weight factor increases by $0.1(1.01)^l$ for each lift increment
numAircraft	the number of aircraft available for the training day [aircraft]
numStudents	the number of students available for the training day [personnel]
numInstructors	the number of instructors available for the training day [personnel]
aircraftcapacity	the maximum number of student and instructor jumpers allowed on a lift [personnel
minLoad	the minimum number of students required for a lift [personnel]
maxPass	the number of student jumpers allowed per pass on a given lift [personnel]

3. Decision Variables

$ST_{l,s,jmp,a}$	binary variable with value 1 if student *s* is assigned to lift *l* during jump *jmp* on aircraft *a*
$IN_{l,i}$	binary variable with value 1 if instructor *i* is assigned to lift *l*
$AC_{l,a}$	binary variable with value 1 if aircraft *a* is assigned to lift *l*
$WAIT1_{l,a}$	continuous variable (binary because of model structure) with value 1 if aircraft *a* must wait on tarmac at least one period (5 minutes) after lift *l*
$WAIT2_{l,a}$	continuous variable (binary because of model structure) with value 1 if aircraft *a* must wait on tarmac at least two consecutive lifts (10 minutes) after lift *l*

4. Objective Function

$$MIN \sum_{l,a|ero_a \neq |L|} w1_l AC_{l,a} + \sum_{\substack{l,a|ero_a \neq |L| \\ \cap l < fuel_a}} 10 w1_l WAIT1_{l,a} + \sum_{\substack{l,a|ero_a \neq |L| \\ \cap l < fuel_a}} 100 w1_l WAIT2_{l,a} + \sum_{l,i} 0.1 IN_{l,\mathrm{i}} + \sum_{\substack{l,s,jmp,a| \\ jmp \leq |J| \\ \cap ero_a \neq |L|}} w2_l ST_{l,\mathrm{s,jmp,a}}$$

5. Subject To

$$1 - AC_{l,a} \geq \sum_{k|\mathrm{k>l} \cap \mathrm{k<l+act}_a} AC_{k,a} \qquad \forall l, a \,|\, ero_a \neq |L| \tag{1}$$

$$1 - \sum_{a|ero_a \neq |L|} ST_{l,s,jmp,a} \geq \sum_{\substack{k,jjmp,a|\mathrm{k>l} \\ \cap \mathrm{k<l+sct}_{jmp} \\ \cap \mathrm{jjmp \leq numjumps} \\ \cap ero_a \neq |L|}} ST_{\mathrm{k},s,jjmp,a} \qquad \forall l, s, jmp \,|\, jmp \leq |J| \tag{2}$$

$$\sum_{l,a|ero_a \neq |L|} ST_{l,s,jmp,a} = 1 \qquad \forall l, jmp \,|\, jmp \leq |J| \tag{3}$$

$$\sum_{\substack{jmp,a|ero_a \neq |L| \\ \cap jmp \leq |J|}} ST_{l,s,jmp,a} \leq 1 \qquad \forall l, s \tag{4}$$

$$\sum_{a|ero_a \neq |L|} AC_{l,a} \leq 1 \qquad \forall l \tag{5}$$

$$maxPass_a \; AC_{l,a} \geq \sum_{s,jmp|jmp \leq |J|} ST_{l,s,jmp,a} \qquad \forall l, \mathrm{a} \,|\, ero_a \neq |L| \tag{6}$$

$$minLoad \; AC_{l,a} \leq \sum_{s,jmp|jmp \leq |J|} ST_{l,s,jmp,a} \qquad \forall l, \mathrm{a} \,|\, ero_a \neq |L| \tag{7}$$

$$\sum_{s,jmp|jmp \leq |J|} ST_{l,s,jmp,a} + \sum_i IN_{l,i} \leq aircraftCapacity \qquad \forall l, a \,|\, ero_a \neq |L| \tag{8}$$

$$\sum_i IN_{l,i} \geq \sum_{s,jmp|jmp \leq |J|} ST_{l,s,jmp,a} \qquad \forall l, a \,|\, ero_a \neq |L| \tag{9}$$

$$\sum_{i} IN_{l,i} \geq 2 \sum_{a|ero_a \neq |L|} AC_{l,a} \qquad \forall l \tag{10}$$

$$AC_{l,a} = 0 \qquad \forall l,a \,|\, l - ero_a \geq fuel_a \cap l - ero_a \leq fuel_a + 12 \cap ero_a \neq |L| \tag{11}$$

$$AC_{l,a} = 0 \qquad \forall l,a \,|\, l \leq ero_a \cap ero_a \neq |L| \tag{12}$$

$$\sum_{\substack{k|k>l-act_a \\ \cap k \leq l}} AC_{\mathrm{k},a} \geq 1 - WAIT1(l,a) \qquad \forall l,a \,|\, l > ero_a \tag{13}$$

$$\sum_{\substack{k|k>l-act_a-1 \\ \cap k \leq l}} AC_{\mathrm{k},a} \geq 1 - WAIT2(l,a) \qquad \forall l,a \,|\, l > ero_a \tag{14}$$

The model determines student, instructor, and aircraft assignment ($ST_{l,s,jmp,a}$, $IN_{l,i}$, and $AC_{l,a}$, respectively) to lift segment, *l*, for a given training day, while minimizing the length of the training day and the aircraft dwell time ($WAIT1_{l,a}$ and $WAIT2_{l,a}$) on the tarmac. This is accomplished through increased penalties, $w1_l$, proportional to the length of the training day and greater penalties for increased aircraft dwell times. Incremental weighs, $w2_l$, are applied to instructor and student load variables to provide incentive for balancing student load and aircraft wait dwell times.

Constraint set (1) sets the aircraft timing by ensuring that an aircraft can only be used once during its aircraft cycle time. Similarly, constraint set (2) sets the student timing by ensuring each student may only jump once during their given student cycle. Constraint sets (3) and (4) ensure that students complete all jumps required during the training day and that no student jumps more than once during the same period. Constraint set (5) allows only one aircraft to be flown in each period. Constraint set (6) assigns students to aircraft and ensures that the number of students allowed on each pass is not exceeded. Constraint set (7) ensures that the aircraft only flies if it has the minimum number of students on board to jump. Constraint set (8) ensures that the aircraft capacity is not exceeded. Constraint sets (9) and (10) ensure that the correct number of instructors is assigned to each aircraft. Constraint set (11) enforces the refueling break required after a set number of lifts for each aircraft. Constraint set (12) ensures that aircraft are only available after ERO for the training day. Elastic constraint sets (13) and (14) establish variables that are penalized in the objective function for instances where aircraft must wait for an excessive time on the tarmac before loading students for the next lift.

C. MODEL VARIATIONS

Different problem instances are run by setting several parameters: the student cycle time, sct_{jmp}, the aircraft cycle time, act_a, and the aircraft ERO, ero_a. The student cycle time is primarily a function of equipment and the number of prepacked student parachutes; the aircraft cycle time is a function of aircraft type; the ERO determines if an aircraft is available, and if so, it determines the expected arrival time of the aircraft. These parameters are the primary means of controlling the scenarios generated by the model.

We also note that this version of the model is capable of producing optimal solutions assuming multiple passes by increasing the *maxPass* variable from 10 to 20 for each aircraft allowed for two passes. Because this version of the model does not determine the number of passes a priori, this model variation only approximates multiple passes and does not account for the increased ACT of 10 minutes for each additional pass. This difference in ACT is not an issue in most cases studied, especially when students have used at least one of the packed chutes available in a two jump day scenario.

The following chapter will describe the parameters in detail. Then, we discuss the findings of the model running based on three scenarios. These scenarios detail the progression of the model as the parameters are updated based on the model results and analysis.

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IV. DATA AND MODEL RESULTS AND ANALYSIS

In this chapter, we describe the data used to populate the model defined in Chapter III and then discuss the model results and analysis. The analysis is based on three scenarios. A scenario is defined as multiple model runs based on different aircraft combinations and jumper equipment configurations.

A. DATA

The parameters for the model were introduced in Chapter III; we discuss the data, i.e., the values of those parameters, in this section.

Student cycle time (SCT) is the total time it takes a student to put on a parachute, jump, assemble, and move back to the personnel shed to begin the process again. Movement from the personnel shed to the aircraft is factored into the aircraft cycle time rather than the SCT. The subcomponents of the SCT are listed and defined below. The amount of time each subcomponent takes in minutes is noted in parentheses.

- Rigging (15)—the student puts on the parachute and attaches any other equipment such as a rucksack, weapon, oxygen cylinders, and mask.
- Jumpmaster Prejump Inspection (JMPI) (2)—the jumpmaster performs a final check on the student to ensure the safety of the student's equipment. Figure 2 depicts an instructor conducting such an inspection.

Figure 2. Jumpmaster Prejump Inspection

A military free fall instructor conducts a jumpmaster prejump inspection (JMPI) on a student to ensure the student has rigged his parachute and equipment safely.

- Drop (5)—the student exits the aircraft, travels through the air, and lands on the ground. During a HAHO jump, an additional seven minutes are added to account for a longer time under canopy, bringing the total drop time to 12 minutes. Figure 3 depicts students exiting the aircraft.

Figure 3. Students Exit Aircraft

Students in orange jumpsuits exit a C-130 aircraft. The instructor on the right will fall beside his student to ensure proper technique is utilized prior to the student deploying his parachute. Photo courtesy of U.S. Army.

- Assemble (10)—once the student has landed, the parachute must be gathered and all other equipment secured. Once this is completed, the student moves to a centralized collection point in the drop zone, depicted in Figure 4.

Figure 4. Drop Zone Rally Point

Once students land and secure their gear, they move to this location to load the bus and return to the personnel shed to continue training.

- Return Drive (10)—the students ride a bus from the drop zone back to the personnel shed.
- Oxygen Exchange (5)—on jumps utilizing oxygen, the students exchange oxygen cylinders after each jump. This exchange takes place along the return route to the personnel shed. (Not required for all equipment configurations.)

- Repack (30)—upon returning to the personnel shed, the students begin to repack their parachute in order to jump again. Figure 5 depicts students repacking their parachutes at the personnel shed. (Not required for all equipment configurations.)

Figure 5. Parachute Repack

Students repack their parachutes inside the personnel shed in order to prepare for another jump.

- Debrief (10)—after each jump, the instructor reviews the student's performance with the student in order to facilitate technical progression.
- Once the students have been inspected, they move from the personnel shed approximately 100 meters to the aircraft. The time this takes may vary 1-3 minutes depending on jumper configuration.

During nighttime operations, an additional 10 minutes are added to the student cycle time for both HALO and HAHO. Table 1 depicts the student cycle time in minutes for each configuration.

Table 1. Student Cycle Time (SCT)

CONFIGURATION	RIGGING	JMPI	DROP	ASSEMBLY	RETURN DRIVE	O2 EX-CHANGE	REPACK	DEBRIEF	SCT
Daytime HALO	15	2	5	10	10	5	30	10	87
Daytime HAHO	15	2	12	10	10	5	30	10	94
Nighttime HALO	15	2	5	10	10	5	30	10	97
Nighttime HAHO	15	2	12	10	10	5	30	10	104

All times are in minutes. HAHO jumps add an additional seven minutes to jumper drop time. Note that the listed times assume the equipment configuration requires repack of parachutes and oxygen exchange.

Aircraft cycle time (ACT), depicted in Table 2, includes loading the aircraft at the personnel shed (depicted in Figures 6 and 7), taking off, climbing to jump altitude, releasing the student jumpers, flying back to the airfield and landing, and finishes with the offload of any passengers. The ACT for a single iteration ends once the aircraft lands and lowers its ramp in anticipation of the next student lift. Typically, the only two types of aircraft the MFFC uses are the C-27 and C-130. The C-27s are organic to the schoolhouse. The pilots are familiar with the system in place at the school, the route they are flying, and the mission requirements. This accounts for the difference in time between C-27s and C-130s. The C-130 is a joint airborne air transportability (JAAT) training aircraft. JAAT aircraft are "free" to the school, as their pilots and crew are conducting their certification training; however, their crews are not always familiar with the requirements of the course. The uncertainty in capabilities is accounted for in the 10 additional minutes factored into the C-130 ACT.

Table 2. Aircraft Cycle Time (ACT)

AIRCRAFT	ACT (1 PASS ONLY)	ACT (2 PASSES)
C-27	20 minutes	26 minutes
C-130	30 minutes	40 minutes

Table 2 depicts the ACT for C-27 and C-130 for either one pass or two passes for each takeoff and student load. One pass is when the aircraft drops all students at the same time; two passes is when only a partial load of students is dropped and then the aircraft circles around and drops the rest.

Figure 6. Movement to Aircraft

Students and instructors walk 100 meters from the personnel shed to the aircraft loading point.

Figure 7. Loading Aircraft

Students and instructors conduct an engine running on-load (ERO) on a C-27.

The smaller size of the C-27 adds time to the loading process compared to the C-130. Dwell time, while the aircraft waits on the tarmac with engines running, is not included as part of the aircraft cycle time. The typical jump altitude for students is 12,500 feet. This varies depending on where the students are in the jump progression, defined in Chapter 1. Both aircraft require one hour for refueling operations. The C-27 can fly nine lifts before it requires a refueling break. The C-130H can fly seven lifts, and the C-130J can fly 13 lifts before it needs to refuel. Because the MFFC does not know what type of C-130 will arrive until the scheduled jump day, all C-130 timings are based on the C-130H model.

Similar to the student cycle time, the instructor cycle time (ICT) is the total amount of time it takes the instructor to don a parachute, jump, assemble, move back to the personnel shed, debrief a student, and get ready to start the process again. The ICT is much shorter due to instructor proficiency under canopy, thus reducing the amount of time in descent and assembling. Instructor proficiency also eliminates the need for an additional 10-minute buffer during nighttime operations.

Additionally, contract parachute packers pack the instructor parachutes. This allows the instructors to focus on debriefing and inspecting students' equipment. The ICT is not a planning consideration here, as it is so much shorter than the SCT for the student equipment configurations under consideration. Table 3 depicts the total instructor cycle time for both configurations for reference.

Table 3. Instructor Cycle Time (ICT)

CONFIGURATION	**ICT**
HALO	36
HAHO	46

ICT for both jump configurations in minutes. ICT is much shorter than SCT, due to instructor canopy proficiency and the use of contract parachute packers.

B. MODEL RESULTS AND ANALYSIS

This section discusses the results of two scenario runs of the manifest model. First we describe the similarities found between the two scenarios. Next we describe each scenario individually, present the results of the scenario, and provide analysis. Finally, we offer an overall analysis of the manifest model output.

1. Scenarios Overview

There are several parameters and other commonalities found in all scenarios, which we introduce here. For example, we assume one JAAT C-130 and up to two organic C-27s in various combinations are available. Each aircraft flies one pass only and the jumpers conduct two jumps per day unless specified otherwise. As previously mentioned, the ACT for the C-130 is 30 minutes, the ACT for the C-27 is 20 minutes, and each aircraft requires a 60-minute refuel break. The SCT is a function of the jumper configuration. Jumper configurations for both scenarios are explained in Table 4. The maximum number of students allowed per lift is 10, and the minimum number is six.

Table 4. Jumper Configuration

Configuration	Name	Description
HA	Hollywood	Standard HALO jump with no additional equipment
HAEO	Wall locker	HALO jump with oxygen and combat equipment consisting of rucksack and weapon
HAEON	Night wall locker	Same as wall locker but under hours of limited visibility
SAEO	Standoff	HAHO jump with oxygen and combat equipment consisting of rucksack and weapon

All jumper configurations utilized by the model. Jumper configuration is defined by the equipment the student is wearing, the type of jump the student is conducting, and the time of day the jump is being conducted.

2. Scenario 1—Baseline 60-Person Class Using MC-4 Parachutes

The first scenario is based on a 60-person class. We assumed each jumper would have one packed MC-4 parachute. The model ran 15 versions with different jumper equipment configurations and aircraft combinations. We used four aircraft configurations: a single C-27, a single C-130, a combination of a C-27 and a C-130, and two C-27s. Nine of the runs are for two jumps per student per day; the other six are for three jumps per student per day. Jumper equipment configurations are depicted in Table 4. The 15 aircraft and jumper configurations are listed in Table 5.

Table 5. Scenario 1 Aircraft/Jumper Configurations

Configuration #	Aircraft/Jumper Configuration
1	1 C-27 & 1 C-130 2 Jumps HAEON
2	1 C-27 2 Jumps HAEON
3	1 C-130 2 Jumps HAEON
4	2 C-27 2 Jumps HAEON
5	2 C-27 3 Jumps SAEO
6	1 C-27 & 1 C-130 3 Jumps SAEO
7	2 C-27 3 Jumps HAEO
8	1 C-27 & 1 C-130 3 Jumps HAEO
9	2 C-27 2 Jumps HAEO
10	2 C-27 3 Jumps HA
11	1 C-27 & 1 C-130 3 Jumps HA
12	1 C-27 & 1 C-130 2 Jumps HA
13	2 C-27 2 Jumps HA
14	1 C-130 2 Jumps HA
15	1 C-27 2 Jumps HA

The different aircraft and jumper configurations used for the model in Scenario 1. The column on the left numbers each configuration and is referenced in the text.

In general, the model shows that the minimum duty day length is 2:50 and the longest day lasts 6:55. The average duty day length for the 15 configurations is approximately 4:30.

Prior to this model, the standard practice for the school was put to the maximum number of students on the aircraft for each lift. This practice creates excessive aircraft dwell time, as the students cycle through jumping faster than they can repack their parachutes and board for the next jump. When dwell time is not planned for, the pilots must wait an unknown amount of time for students. This causes great strain on the aircraft and increases maintenance issues. It also wastes money, as every hour of blade time costs $4,500 whether the students are jumping or not. When only one aircraft is used in this scenario, there is no planned dwell time; however, when more than one aircraft is used, the planned dwell time varies from 10 minutes to as long as 55 minutes. The average amount of planned dwell time for the multiple aircraft configuration is 28 minutes. This model determines the optimal number of students to put on each lift to balance the tradeoff of reduced dwell time blocks and the overall aircraft operational day.

The manifest model shows that some dwell time is unavoidable with certain aircraft and jumper configurations. The MFFC now understands more fully the tradeoff between aircraft dwell time and the aircraft operational day and, more importantly, can quantify the "planned" dwell time necessary given the aircraft available and the training requirement for a given training day. As previously discussed, the MFFC is not the only course operated at YPG. Occasionally, the other courses utilize MFFC aircraft to complete their missions; if the MFFC knows what dwell time they will have and when, those aircraft become available to other courses during those blocks. These planned blocks of dwell time could also be used for instructor certification and currency operations for personnel stationed at YPG.

The model output has been consolidated and put into a timeline like that shown in Table 6. Table 6 depicts the four runs of the nighttime wall locker jump, or HAEON configuration, configurations number one through four of Table 5. This configuration is selected for detailed discussion because of the resulting differences in the duty day length, planned dwell time, number of students per lift, and refueling.

Table 6. Scenario 1 Four Aircraft Configurations of the Nighttime Wall Locker Jump

Time in 5 minute intervals	Total Time	0	5	10	15	20	25	30	35	85	90	95	100	105	160	165	185	190
1xC27 & 1xC130 2 Jumps HAEON	3:00			C27_1 (10)				C27_1 (10)						C27_1 (10)		C27_1 (6)		
		C130 (10)							C130 (10)				C130 (6)		C130 (6)			

Time in 5 minute intervals	Total Time	0	5	10	15	20	160	165	170	175	180	235	240	280	300
1xC27 2 Jumps HAEON	4:55	C27_1 (10)				C27_1 (10)	C27_1 (10)						C27_1 (10)	C27_1 (10)	

Time in 5 minute intervals	Total Time	0	5	10	15	20	25	30	180	185	190	195	200	205	210	265	270	390	420
1xC130 2 Jumps HAEON	6:55	C130 (10)						C130 (10)	C130 (10)								C130 (10)	C130 (10)	

Time in 5 minute intervals	Total Time	0	5	10	15	20	25	30	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	170	175
2xC27 2 Jumps HAEON	2:50	C27_1 (10)				C27_1 (10)			C27_1 (6)											C27_1 (10)				C27_1 (8)				C27_1 (6)		
				C27_2 (10)				C27_2 (10)			C27_2 (10)							C27_2 (10)				C27_2 (10)					C27_2 (6)			

	REFUEL TIME
	DWELL TIME
	END OF DUTY DAY
	BREAK IN TIME

The model output for all four aircraft configurations of the nighttime wall locker (HAEON) jump in a timeline format. The time is blocked in five-minute intervals. Due to the length of the timeline, parts with no significant material are removed, signified by the green lightning bolts. In the cases of multiple aircraft, the aircraft are numbered in the timeline under the time interval. For example, in the first timeline, one C-27 and one C-130 are available. The number in parenthesis below the aircraft is the number of students on the aircraft for that pass. The red blocks mark planned aircraft dwell time. For example, the two C-27 line has a 35-minute planned dwell time block for one aircraft and a 15-minute planned dwell time block the other. The yellow blocks signify a break for refueling. The model determines the best student load so that both the planned aircraft dwell time and the aircrew day are minimized. The lifts highlighted by green circles indicate changes in the number of students per lift, and the end of the duty day is signified by the black blocks.

As shown in the first three timelines of Table 6, the runs that utilize a single aircraft do not show much variation in the student load from the maximum capacity of 10 students per lift. Since only one aircraft is being used, there is more than enough time between lifts for 10 students to be ready for the next lift. A one-hour refueling period is also required when only one aircraft is used. The refueling period is only depicted twice in the sample in Table 6; however, it occurs in nine of the 15 configurations run in Scenario 1. Also not shown here is the fact that there is no planned dwell time in any of the single aircraft configurations, regardless of jumper configuration.

The planned dwell time appears only in the multiple aircraft configurations. Of the four runs shown, the 2x C-27 HAEON configuration depicted in Table 6 has the longest continuous block of planned dwell time. After the third lift, C-27_1 has 35 minutes of planned dwell time. During that period, C-27_2 also has a 15-minute segment of planned dwell time. C-27_2 passes C-27_1 and holds that position in the lift order for the duration of the duty day. This leap-frogging also occurs in other aircraft configurations, primarily in the C-27/C-130 combinations, because of the C-27's shorter ACT.

The students per lift changes between lifts in some cases where multiple aircraft are used. As highlighted by the green circles in Table 6, the students per lift range from the maximum of 10 to as few as six. The first several lifts are set to the maximum lift capacity, and then the number of students per lift varies to facilitate a smooth transition between lifts and to minimize planned dwell time. As mentioned in the summary results, many of the configurations in this first scenario resulted in the same or very similar total times for the duty day. Six runs had a range of 20 minutes, from 2:50–3:10. Four fell within five minutes of each other, from five hours to 5:05. The similarities of the total times provided insights which allowed us to make some simplifying assumptions concerning the second scenario, discussed in the next section.

3. Scenario 2—Baseline 80-Person Class Using RA-1 Parachutes

The general scenario assumptions are still applicable; however, Scenario 2 incorporates modifications based on feedback from the MFFC. The first modification increases the number of students from 60 to 80. The second modification accounts for a new parachute the students are using, the RA-1. The RA-1 parachute has a longer glide ratio, which means the rate of descent is slower than with the MC-4. This essentially adds eight minutes to the student cycle time, as the student is in the air under canopy for a longer time. Because more RA-1s than MC-4s are available to the students, the MFFC determined that each student would have two packed RA-1s at the beginning of the jump day instead of only one MC-4, reducing the SCT by 30 minutes. Due to the increased class size and the resulting stress on instructors, the MFFC determined that the students would not jump more than twice per day.

From insights gained in Scenario 1, we reduced the number of jumper and aircraft configurations to eight, as referenced in Table 7. Note that this scenario only uses two aircraft configurations, two C-27s and the C-27/C-130 combination, as the single aircraft cases do not provide additional information to what we have already learned. Along with the standard configurations from Scenario 1, we investigated an additional configuration of aircraft and number of jumps to better understand the effects of additional passes per lift on aircraft operational day and dwell time.

Table 7. Scenario 2 Aircraft/Jumper Configuration

Configuration	**Aircraft/Jumper Configuration**
1	1 C-27 2 Jumps (2 passes) HA
2	2 C-27 2 Jumps HA
3	1 C-27 & 1 C-130 2 Jumps HA
4	2 C-27 2 Jumps HAEO/SAE
5	1 C-27 & 1 C-130 2 Jumps SAEO/HAEN
6	2 C-27 2 Jumps SAEO/HAEN
7	1 C-27 & 1 C-130 2 Jumps HAEN

The different aircraft and jumper configurations used for the model in Scenario 2. The column on the left numbers each configuration and is referenced in the text.

In general, the minimum duty day length is 4:20, and the longest day lasts 6:30; however, that is for a nonstandard run. The longest day for the standard configuration is 4:45, and the average duty day length for the six standard configurations is approximately 4:30. There is no planned dwell time identified for any of the Scenario 2 configurations, as we will discuss in the following paragraphs. All seven configurations require a refueling break.

The two runs depicted in Table 8 show the nighttime wall locker jump and the daytime standoff wall locker jump. Of note, the two C-27 configuration duty day is 4:40, and the C-27/C-130 combination takes five minutes longer at 4:45. In the two C-27 configuration, both aircraft require a refuel break. Following the break, only one lift remains for the first C-27, while the second C-27 has two. In the C-27/C-130 configuration, the C-27 requires a refuel break followed by two lifts; the C-130 does not refuel or do another lift. The duty day is shorter this way than if the C-130 refuels.

Table 8. Scenario 2 Multiple Aircraft Configurations of the Nighttime Wall Locker Jump and the Daytime Standoff Jump

Time in 5 minute intervals	Total Time	Aircraft	0	5	10	15	20	25	30	35	40	45	180	185	235	240	245	260	265	270	275	280
2C27 2 Jumps SAEO/HAEN	4:25	C27_1	0	10	0	0	0	8	0	0	0	6	0	0	0	0	8	0		0	0	0
	4:40	C27_2	10	0	0	0	10	0	0	0	6	0	0	0	0	10	0	6	0	0	0	

Time in 5 minute intervals	Total Time	Aircraft	0	5	10	15	20	25	30	35	60	65	180	185	215	220	225	230	235	240	290
1C27&1C130 2 Jumps SAEO/HAEN	4:45	C27_1	10	0	0	0	10	0	0	0	6	0	0	0	0	0	0	0	0	10	
	3:35	C130	0	10	0	0	0	0	0	10	0	6	0	10		0	0	0	0	0	0

REFUEL TIME (yellow)
END OF DUTY DAY (black)
BREAK IN TIME (green lightning bolt)

The model output for the 2x C-27 and C-27/C-130 configurations of the nighttime wall locker (HAEON) jump and daytime standoff (SAEO) jump in a timeline format. The time is blocked in five-minute intervals. Due to the length of the timeline, parts with no significant material were removed, signified by the green lightning bolt. The aircraft type is listed under the Aircraft heading. The number listed below the time increment is the number of students on that lift. The yellow blocks signify a break for refueling, and the end of the duty day is signified by the black blocks.

The first nonstandard run, one C-27 doing two passes per lift, is depicted in Table 9. When an aircraft conducts two passes per lift, it flies over the drop zone, drops an initial group of jumpers, then circles around to the drop zone again without landing and drops the final group of jumpers. This explains the higher number of students per lift at 15. The final lift is 10 students, because there are only 10 left to jump. This run results in a six-and-a-half hour duty day but yields no planned aircraft dwell time. Based on preliminary analysis, it appears that two passes per lift, when two aircraft are available, is not efficient. This is because the SCT is extended and one aircraft is always available to take the next load. The result is that in the multiple aircraft case, the model never wants load more than 10 students on consecutive passes, which indicates that doing so would cause excessive dwell time. In the event there is only one aircraft available to the MFFC, doing two passes per lift may be efficient, because students have enough prepacked chutes to keep the SCT very short throughout the training day.

The same parameters were applied to the single C-130 configuration; however, it proved infeasible, as the training day would exceed the eight-hour flight day requirement for the pilots.

Table 9. Scenario 2 Nonstandard Run #1 C-27 Two Passes per Lift

Time in 5 minute intervals	Total Time	Aircraft	0	5	10	15	20	25	30	180	235	240	360	365	370	375	380	385	390
1xC27 2 Jumps (2 passes) HA	6:30	C27_1	15	0	0	0	0	0	15	0	0	15	10	0	0	0	0	0	

(yellow)	REFUEL TIME
(black)	END OF DUTY DAY

(green lightning bolt) BREAK IN TIME

The model output for the first nonstandard lift run by the model, a single C-27 doing two passes per lift. The time is blocked in five minute intervals. Due to the length of the timeline, parts with no significant material were removed, signified by the green lightning bolt. The aircraft type is listed under the Aircraft heading. The number listed below the time increment is the number of students on that lift. In this case, the number of students is raised to 15 to accommodate two passes per lift. The yellow blocks signify a break for refueling, and the end of the duty day is signified by the black blocks. While no aircraft dwell time was identified, it seems that running two passes per lift when two aircraft are not available is inefficient.

Many of the findings from Scenario 1 are applicable to Scenario 2. In Scenario 1, the average planned dwell time per configuration is 28 minutes, whereas in Scenario 2 it is zero. The major difference between the scenarios is that the students have two packed parachutes in Scenario 2. This results in there being no planned dwell time. The average duty day increases 20 minutes between Scenario 1 and Scenario 2. We attribute this to increasing the total number of students in the class from 60 to 80.

C. APPLICATION TO THE MFFC

The MFFC used the model output to validate a new course of action developed by MFFC staff for day-to-day operations to mitigate instructor fatigue. Originally, the course offered 20 classes of 60 students each per year. Each class had two weeks of overlap, which included a week where two classes of students conducted jumps each day. The strain on the instructors led to multiple injuries. The MFFC proposed instead offering 15 classes of 80 students each per year. This proposal reduces the class overlap to one week with no jump overlap.

The MFFC staff split the number of students in half based on our analysis of the model output. Master Sergeant Timothy Groves, the Non-commissioned Officer In Charge at the MFFC, describes the course of action: “Both groups of students show up at the same time. Jumpers from the first group load lift one, while jumpers from the second group get ready for lift two. By rotating groups each lift, unplanned dwell time is eliminated, as there are jumpers ready to load the plane as it lands. This course of action also facilitates more individual instructor time with each student" (Groves, personal communication, 2016). The model proved that by utilizing the aircraft in the specified manner, 81 students could complete two jumps within six and a half hours. According to Major Enke, the MFFC commander, the model output "showed potential duty days that we didn't think were possible. It made the MFFC take a hard look at how we were using our resources" (J. Enke, personal communication, 2016).

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V. RECOMMENDATIONS AND CONCLUSIONS

The value of the military free fall scheduling and manifest optimization model is the insights it provides the decision makers at the MFFC. Major Enke, the MFFC commander, states "the model helped us determine the biggest constraint is the use of aircraft and how to most efficiently utilize them to maximize student throughput" (J. Enke, personal communication, 2016).

The most important finding determines the optimal number of students per lift. Reducing the number of students to less than the maximum capacity of the aircraft allows minimal aircraft dwell time. The second scenario identifies no planned dwell time, which in theory will save the school thousands of dollars in wasted blade time per duty day. In addition to reducing operating costs, the model analysis also validates a new course of action developed by MFFC staff for day-to-day operations to mitigate instructor fatigue, described in Chapter IV. The MFFC staff took the model output and used the product as left and right limits on how to get 80 students to jump a specified number of times per day (J. Enke, personal communication, 2016).

Running multiple passes with multiple aircraft does not appear to increase efficiency when students have enough prepacked chutes to cover all their scheduled jumps for the day. This is because the SCT has been extended, even with two packed parachutes, which means the duty day lengths are similar to those associated with only one aircraft. It makes the most sense, therefore, to only run one pass per lift in order to streamline the duty day, unless the MFFC only has one aircraft available that day, which facilitates two passes.

Planned dwell time, in scenarios in which it occurs, permits the pilots to avoid sitting on the runway with the engines running. Instead, after dropping the lift of jumpers, they can continue flying until the next lift of students is ready to be picked up. Planned dwell time additionally allows the flight crew to do any number of other tasks, as the gap in training can be anticipated. The model also lets aircrew know when they will do two lifts in a row, allowing the other aircraft to move out. Major Enke said the data used for the model was presented to the pilots by the MFFC staff to see if it was possible to modify flight patterns to “shave some time off the ACT.” The model analysis provided a target aircraft usage the MFFC should be striving to achieve (J. Enke, personal communication, 2016).

In conclusion, the model analysis allowed the decisions makers at the MFFC to determine the best way to run an 80-student class with the RA-1 parachute ahead of their original implementation deadline. The analysis also provided left and right limits and then mathematical validation to the current course of action being executed. Future versions of this model could be applied to other training courses facing scheduling dilemmas, hopefully with similar results.

LIST OF REFERENCES

Budiansky, Stephen. 2013. *Blackett's War: The Men Who Defeated the Nazi U-Boats and Brought Science to the Art of Warfare*. New York: Alfred A. Knopf.

Department of the Army. 2005. *Special Forces Military Free-Fall Operations* (FM 3-05.211). Washington, DC: Headquarters, Department of the Army.

Enke, Josh. 2015. *Military Free Fall School (MFFS) Command Brief.* Yuma Proving Ground, AZ: Major Josh Enke, August 10.

Gass, Saul I., and Arjang Assad. 2005. *An Annotated Timeline of Operations Research: An Informal History*. New York: Kluwer Academic.

Hauck, James W. 2002. "The Origins of Military Free-Fall Parachuting in U.S. Army Special Forces." In *Special Forces: The First Fifty Years*. Tampa, FL: Faircount.

Hillier, Frederick S. and Gerald J. Lieberman. 2010. *Introduction to Operations Research*. 9th ed. New York: McGraw Hill Higher Education.

INFORMS. 2015. "World's Best Analytics Teams Selected for 2016 INFORMS Franz Edelman Award Competition." December 14. https://www.informs.org/About-INFORMS/News-Room/Press-Releases/2016-Edelman-Finalist-Announcement.

Mazzetti, Mark, Nicholas Kulish, Christopher Drew, Serge F. Kovaleski, Sean D. Naylor, and John Ismay. 2015. "SEAL Team 6: A Secret History of Quiet Killings and Blurred Lines." *New York Times,* June 7. http://www.nytimes.com/2015/06/07/world/asia/the-secret-history-of-seal-team-6.html?_r=0.

Owen, Karla. 2008. "Military Free Fall Team Makes Own History." Internet Archive, August 22. http://web.archive.org/web/20090106051528/http:/news.soc.mil/releases/News%20Archive/2008/August/SP-080822-01.html.

Ragsdale, Cliff T. 2008. *Spreadsheet Modeling and Decision Analysis*. 6th ed. Mason, OH: South-Western College.

Sutherland, Ian D. 1990. *Special Forces of the United States Army, 1952–2002*. San Jose, CA: Bender.

United States Army John Fitzgerald Kennedy Special Warfare Center and School. 2015. *Military Free Fall Expansion.* Fort Bragg, NC: USAJFKSWCS, July 31.

Weeks, John. 1976. *Airborne Equipment: A History of Its Development*. New York: Hippocrene Books.

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