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Optimization of daily flight training schedules

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

OPTIMIZATION OF DAILY FLIGHT TRAINING SCHEDULES

by

Roger S. Jacobs

March 2014

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The daily flight schedule at Training Air Wing-Two (TW-2) is built manually each day by squadron scheduling officers (SKEDSOs). They rely on their intuition, experience and sound judgment to output a flight schedule. Each SKEDSO spends eight hours a day on this task, but currently there is no measure of the efficiency a given flight schedule. Our goal is to enhance the current planning process by alleviating many of the tedious tasks through an automated optimization program. To that end, this research develops Flight Training Scheduler (FTS), an optimization-based tool, to aid the SKEDSO in production of daily flight schedules. FTS allows the SKEDSO to place an objective, value-oriented metric on the total events scheduled. A typical instance of this problem for TW-2's Phase II students consists of approximately 30 students, 65 flight events and 35 instructor pilots. FTS provides fast, automated guidance to the SKEDSOs that can help them increase throughput of students in the advanced strike training syllabus.

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OPTIMIZATION OF DAILY FLIGHT TRAINING SCHEDULES

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The daily flight schedule at Training Air Wing-Two (TW-2) is built manually each day by squadron scheduling officers (SKEDSOs). They rely on their intuition, experience and sound judgment to output a flight schedule. Each SKEDSO spends eight hours a day on this task, but currently there is no measure of the efficiency a given flight schedule. Our goal is to enhance the current planning process by alleviating many of the tedious tasks through an automated optimization program. To that end, this research develops Flight Training Scheduler (FTS), an optimization-based tool, to aid the SKEDSO in production of daily flight schedules. FTS allows the SKEDSO to place an objective, value-oriented metric on the total events scheduled. A typical instance of this problem for TW-2's Phase II students consists of approximately 30 students, 65 flight events and 35 instructor pilots. FTS provides fast, automated guidance to the SKEDSOs that can help them increase throughput of students in the advanced strike training syllabus.

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LIST OF ACRONYMS AND ABBREVIATIONS

CQ	carrier qualification
CNATRA	Commander Naval Air Training
COMTRAWINGONE	Commander Training Wing One
COMTRAWINGTWO	Commander Training Wing Two
FIST	Flight Instructor Standardization and Training Matrix
FTS	flight training scheduler
GAMS	General Algebraic Modeling System
LSO	landing signal officer
OPSO	squadron operation officer
SKEDSO	squadron schedule officer
TIMS	Training Integrated Management System
TW-2	Training Air Wing Two
VT-22	Training Squadron Twenty Two

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EXECUTIVE SUMMARY

The daily flight schedule at Training Air Wing-Two (TW-2) pairs instructor pilots with student naval aviators to achieve syllabus events. The schedule is built manually each day by squadron scheduling officers (SKEDSOs). They rely on their intuition, experience and sound judgment to output a flight training schedule. SKEDSOs must track each student individually through the syllabus while managing multiple business constraints, including: instructor qualification requirements in each training phase; instructor and student flight per-day limits; aircraft carrier availability dates; weapons detachment dates; syllabus flow; student warm-up window; instructor pilot requirements for each event; time-to-train limits; and, instructor availability. The SKEDSOs attempt to manage these constraints in order to maximize output, that is, students completing the syllabus (or advancing as far as possible). A typical instance of this problem for TW-2's Phase II students consists of approximately 30 students, 65 flight events and 35 instructor pilots. Each SKEDSO spends eight hours a day on this task, but currently there is no measure of the efficiency a given flight schedule.

In this thesis, we develop Flight Training Scheduler (FTS). FTS is a mixed-integer, linear, mathematical optimization model that addresses the need for a fast, automated scheduling tool, capable of producing solutions with quantifiable output metrics. FTS has been tested and evaluated. Current and former squadron schedule and operation officers have been asked for input and many of their suggestions have been incorporated into FTS.

Using FTS has three main benefits:

1. FTS produces a daily schedule in 30 minutes versus 16 SKEDSO-hours. A reduction in the time to produce the daily schedule may lower manpower costs for the Navy. Additionally, when entire schedules are canceled for any reason, FTS can rapidly respond with a new daily schedule, which accounts for these lost events.
2. FTS produces a seven-day schedule versus one-day schedule, allowing FTS to anticipate future event requirements. Since FTS is considering the effects of the current-day's schedule on future daily schedules, its output

are more efficient. FTS ensures that students meet time critical gates by accelerating their training and accelerating other students to train as pairs.

3. FTS allows the SKEDSO to place a value-oriented metric on the total events scheduled. This gives SKEDSOs an objective, quantitative measure for comparison among different schedules, and the ability to assess the impact of event cancelations or substitutions.

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I am especially gratefully to the people who contributed to this work both directly and indirectly. My wife, Jenny, has shouldered the burden of many of the household duties during this challenging academic portion of my career. I am blessed that she has been there as a sounding board for the past 14 years. She has been a wonderful mom to my children and is raising two terrific kids. My daughter, Kali, and son, Jackson, are a welcome relief and have provided us with a tremendous amount of joy.

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Thanks to my small section of U.S. classmates, Miley, Dave, Brett, Brennan, Jeffrey, Trisha and Sarah. There was never a time you all did not make yourselves available whenever anyone in the section needed an extra hand with academics or simply a baby sitter on Friday night. I wish you all fair winds and following seas in your future duty assignments.

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I. INTRODUCTION

A. PURPOSE

Training Air Wing Two (TW-2) is located on Naval Air Station Kingsville, Texas. TW-2 consists of two squadrons, Training Squadron Twenty One and Training Squadron Twenty Two (VT-22). A squadron consists of a cadre of instructor pilots, students and training aircraft. Each squadron is tasked with the production of the Navy's future aviators. Together, these two squadrons produce half of all Navy carrier-qualified pilots in the fleet today.

Each day at TW-2 a flight schedule is produced by squadron scheduling personnel. This process involves two dedicated schedule officers (SKEDSOs) per squadron pairing students with qualified instructors. They rely on their intuition, experience and sound judgment to output a flight training schedule. Their goal is to produce a schedule with a high number of student-completed events. They build the flight schedule manually assigning one instructor-student pair at a time.

Consideration is given to which instructor flies with which student; however, the number of possible pairs makes it impossible for the SKEDSO to determine if he or she generating the best pairings, so there is no measure of the efficiency a given flight schedule.

A simple example of an inefficient schedule follows. Consider three students: "A," who is eligible for event "2," and "B" and "C," who are eligible for event "1." These events must be done in order and we have three instructor-training periods in each day. Events "1" and "2" are single-student events. Event "3" requires two students. A SKEDSO could conceivably produce a suboptimal schedule as detailed in Figure 1.

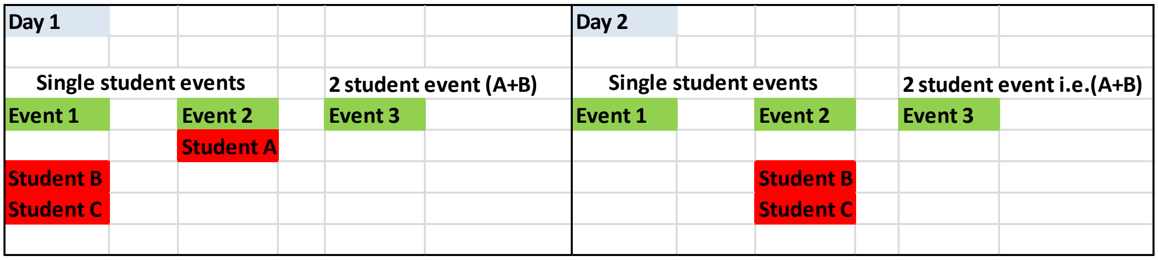

Figure 1. Inefficient two-day schedule

From Figure 1, we observe that, on day “2,” student “A” is eligible to be scheduled for event “3” but the SKEDSO is unable to schedule him or her because there is not another student with whom to conduct this event. This results in one lost training day for student “A,” waiting for student “B” or “C” to complete event “2.” This SKEDSO has under-utilized their available instructor training periods. A more efficient schedule given this scenario is detailed in Figure 2.

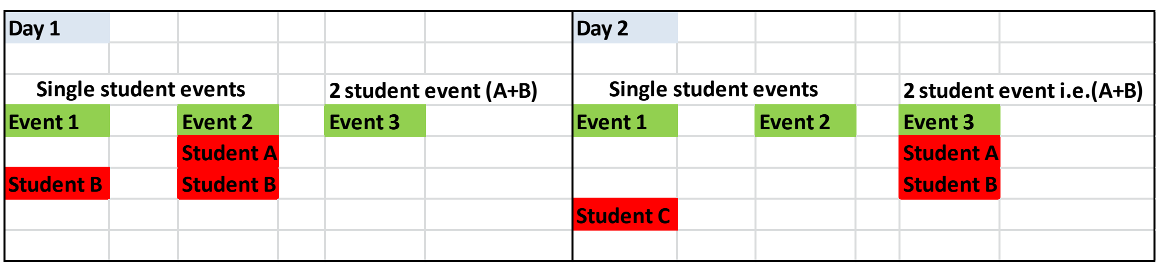

Figure 2. Efficient two day schedule

In Figure 2, student “B” is scheduled for two events on day “1,” subsequently on day “2” both students may be scheduled for event “3.” In addition, student “C” may be scheduled for event “1.” This schedule results in no lost training time for student “A” and no loss instructor-training periods. The SKEDSO is tasked with completing this scheduling decision for tens of students and events simultaneously, a very complicated task.

The SKEDSO desires to move all students through the strike training syllabus taking care that critical “gates,” such as carrier qualification (CQ) dates, are not missed. A failure to schedule a student for enough events early in the training time line may cause the student to miss a critical detachment date. Each student is tracked so these gates are not missed. An optimum schedule would push the highest number of students as far as possible through the syllabus in the shortest period of time. The SKEDSO must strike the proper balance of these competing objectives.

Even the most senior SKEDSOs require multiple iterations in order to meet various constraints. Herein is our goal: to produce an optimization tool that aids the SKEDSO by generating daily flight schedules that maximizes a merit function of event completions. Specifically, this thesis develops Flight Training Scheduler (FTS). FTS is a mixed-integer, linear, mathematical optimization model that addresses the need for a fast, automated scheduling tool, capable of producing quality-measurable solutions.

B. PLANNING PROCESS

The normal process for building the daily schedule begins each morning with the review of the previous day's completed events. These are added to each student naval aviator's completed training line on the squadron schedule board. Each squadron completes approximately 30 to 70 events per day. Once the schedule board is updated, the SKEDSO begins the process of pairing instructors with students for the next day's events. Squadron operation officers (OPSOs) will provide SKEDSOs with priority events (that need to be on the schedule) for various reasons such as CQ detachments, extra instruction flights and winging (completion) dates. All of these high-priority events are part of Phase II of the advanced strike syllabus. After the high-priority events are scheduled, SKEDSOs pair the remaining unutilized instructors and students. Once the SKEDSO reaches a constraint, such as utilizing all instructors to their maximum flights per day limit, the schedule is deemed complete.

SKEDSOs use the squadron flight instructor standardization and training matrix (FIST) to ensure each instructor is qualified to instruct or lead each event. An example of a squadron's FIST is provided in Table 1. We can see the SKEDSOs must manage 29 separate qualifications for each instructor in the squadron. SKEDSOs are also responsible for ensuring instructors and students are provided adequate crew rest and managing instructor and student availability.

In Table 1, the top row lists all the qualifications an instructor may acquire. The first column is a partial list of instructors in VT-22. Non-empty cells (i.e., cells with an "X") indicate that the instructor may instruct or lead that particular type of event.

QUALS COMPLETE REPORT

Unit(s): VT-22 Personnel: ALL Classification: Instructor Pilot
March 25, 2014

I = IUT	Q = Qualified	Black	Expiration>60 days
D = Designated	X = Checker	Green	Expiration between 30 to 60 days
F = Facilitator	S = Stan checker	Blue	Expiration between 15 to 29 days
E = Expired	L = Lead	Orange	Expiration within 14 days
		Red	Expired

37Active 13 Reservist/50 Total	*DAY-ONLY SEC LD					"ANNUAL"						ITU "S"							RESVD										
Rank Full Name	INST	FAM	2FORM	4FORM	NFAM	NFORM	SECT	DIV	1ON	2ON	SLL	WEAPONS	POP	WEAPONLD	OCF	TACF	TACFLD	2ACM	2ACMLD	3ACM	3ACMLD	CQDEMO	LDSF	NFAMCHASE	INSTCK	NATOPSA	NATOPSC	CRM	T45CIP
LCDR B, M.	S	S	S	S	S	S	L	L								I						X	S		D			X	D
Capt C, G.	X	X	X	X	X	X	I		X			X	D																D
Capt C, R	Q	Q	Q	Q	X	Q																							D
Maj D, W.	E	E	E	E	E	E	L	L	X	E	E	E	E	D		E	D							E					E
LT D, G.	X	X	X	X	E	E	L	L							X	X	D	X	D	X		X	L						D
LT D, C.	S	S	S	S	S	S	L	L														X	L	E	D		D	X	D
LT F, J.	X	X	X	Q	X	Q	I															X							D
LCDR F, D.	Q	Q	X	Q	X	X	L		I			I				I													D
LCDR H, R.	E	S	S	S	S	S	L	L	E			E			S	S	D	S	D	S	D	S	S						D
Capt J, R.	X	X	X	X	X	X	L	L														X	L						D
LCDR J, C.	X	X	X	X	E	E	L	L	X	X	X	S	E	D		X	D	X	D	X									D
Capt K, A.	X	X	X	X	X	X	L	L	X	Q	X	X	E			X	D												D

Table 1. FIST example

SKEDSOs must also ensure students follow the Advanced Strike Course Flow. Figure 3 details the complex syllabus flow and the many paths a student may take through the syllabus (Chief of Naval Air and Training [CNATRA], 2010).

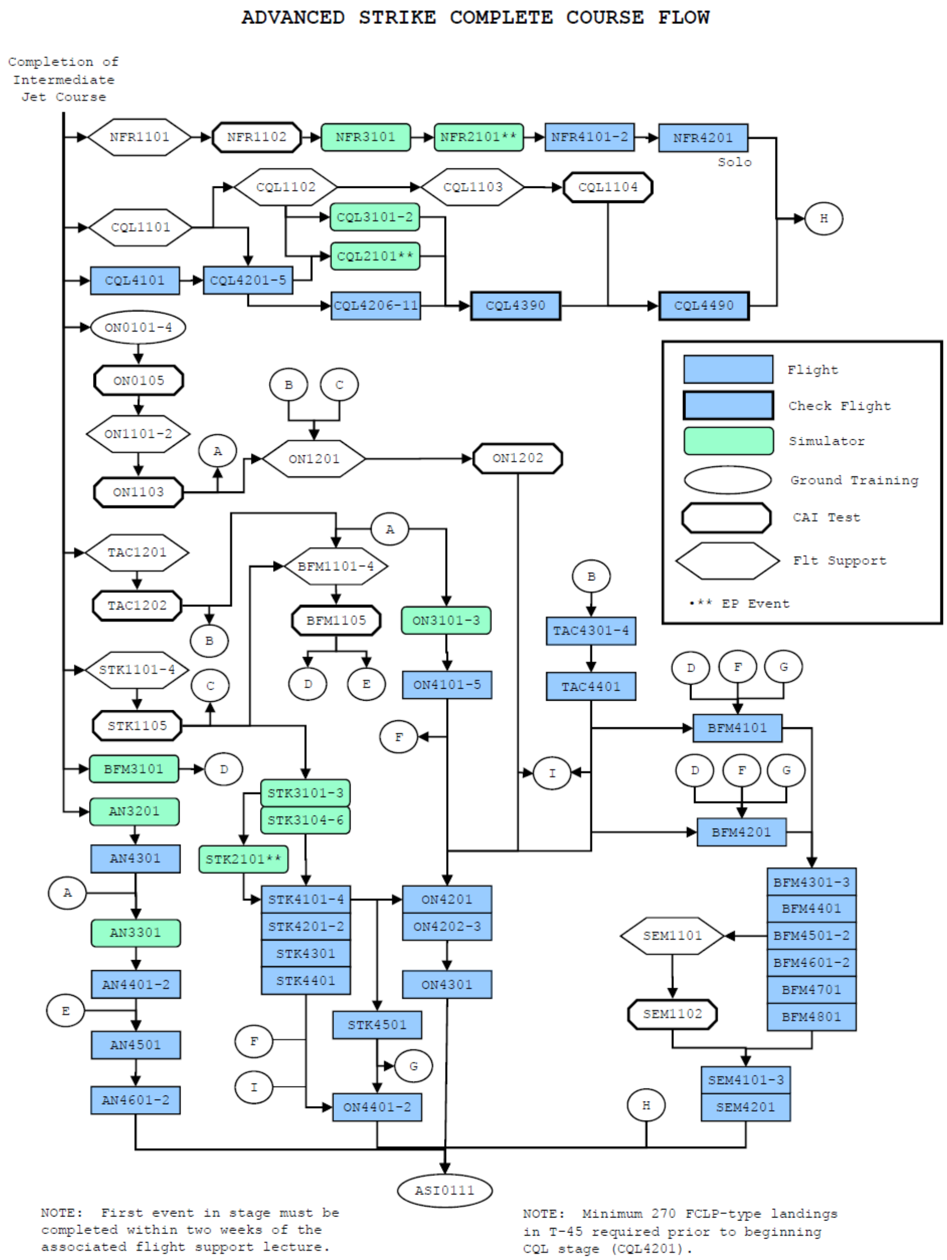

Figure 3. Advanced Strike complete course flow

Figure 3 details all the flight events, represented by blue rectangles that the SKEDSO must schedule in Phase II. These rectangles may represent a single flight event, or many events, depending on the training block. In most blocks a simulator event is required prior to a flight event and are represented by green rectangles. All blocks require a ground training event, represented by a clear oval prior to the first flight or simulator event. The SKEDSO must decide which path is the most efficient for each student.

The process of building the daily flight schedule is very dynamic. The loss of one event on the current day could cascade into the schedule for the following day, necessitating numerous instructor replacements and reassignment of students and jets.

Throughout the construction of the daily flight schedule, the current day's schedule is monitored for completions, cancelations and student-failed flights. The SKEDSO must account for these flights or risk cancelation of the next day's events due to unavailable instructors, thus resulting in two student-training days lost. In addition, the SKEDSO may lose the availability of the now unused jet and the potential loss of an instructor training event. An example of this scenario occurs when a student is scheduled for a formation check flight that is canceled due to weather. The formation check flight certifies that the student is safe for "solo" flight (i.e., without an instructor onboard the aircraft). The following day the student is scheduled for the solo event; however, because the check ride did not take place, the student is not eligible for a solo flight. Only a lead instructor is scheduled and because it is a solo flight no instructor is scheduled for instruction, thus this flight is canceled. The scheduled lead instructor would have been better utilized in another event. An experienced SKEDSO will closely monitor the check rides in order to avoid the loss of events on the following day, assess the effects of canceled events on the next day's schedule, and expeditiously implement a change.

The number of events lost should be kept to a minimum and take into account event type. Events of certain types can be more difficult to reschedule if they require more instructors, meaning a loss would have a larger effect on the next day's schedule. Event types can be critical if the loss would cause a student to fail to meet a winging date. A winging date is an example of a long-range goal that the SKEDSO attempts to meet with each daily schedule. SKEDSOs must determine which events can be rescheduled that will cause the smallest disruption to winging goals, balancing both near- and long-term objectives.

If building an optimum daily flight schedule can be automated, these time-critical changes can be made on a completed schedule giving the SKEDSO a greater amount of time to determine the best substitute events for both students and instructors.

C. PROBLEM SPECIFICATIONS

A strike fighter syllabus of events is used to ensure every student is instructed in all aspects of flight, from the basic skills of airmanship to advanced fighter maneuvers and carrier landings. The skills taught include: formation flying skills, tactical formation skills, low level flight skills, air combat maneuver skills and weapon delivery skills. The syllabus is divided into 131 flight events. 65 of these events take place in Phase II, which is the focus of this research. Each event has specific characteristics including: number of students and aircraft in the event, instructor requirements in the jet(s), lead instructor requirements, additional student requirements, and prerequisite events. Student events are scheduled so that each event builds upon the flight skills learned in the previous events.

1. Event Prerequisites

Events must be sequenced properly to ensure students possess adequate aviation skills to successfully complete them. Precedence relationships are set up between pairs of events. For example, in order to fly tactical formation flights the student must have completed the basic formation stage.

An event may have multiple prerequisites; similarly, the same event may be a prerequisite to multiple events. For example, the tactical formation phase precedes both low-level flights and basic fighter-maneuver flights. Consequently, there are many paths a student may take through the strike training syllabus.

2. Instructor Pilots

The students at TW-2 progress through the syllabus by completing scheduled events with qualified instructors. Each instructor obtains qualifications through a standardization and training program. An instructor must complete the training requirements with a standardization pilot, who is also an instructor. Instructors must keep their qualifications current, that is, they must instruct these events in a set period of time. In addition, the instructor must requalify each year (CNATRA, 2010, pp. 2-4). An instructor is limited to instructing no more than two events each day.

3. Event Cycles

Each day is split into six event cycles for the purpose of maintenance and event scheduling. Maintenance is obligated to provide a set number of jets per cycle. SKEDSOs are obligated to schedule events that use no more than this set number of jets. Each cycle is divided into five-minute launch windows. SKEDSOs must avoid scheduling too many events in each launch window as this will overwhelm launch crews. The duration of each event is roughly equal to a cycle, but its execution may overlap into the next cycle depending on when the event is launched.

4. Carrier Qualification and Landing Signal Officers

When the student enters the CQ phase he or she has already proved proficient enough in the jet to safely land on a 200- by 8,000-foot runway without an instructor. The landing signal officer's (LSO) responsibility is to instruct the CQ students to land inside a carrier box that is painted on the approach end of each runway. The dimensions of the carrier box are 80 feet by 795 feet, simulating the actual dimensions of the landing area on modern-day aircraft carriers.

The CQ phase differs from other phases in that the instructor pilot is not actually in the jet with the student. The LSO is positioned at the approach end of the runway grading each student pass. The LSO is able to instruct up to eight CQ students during the phase. If student loading is increased beyond eight students, two LSOs must be scheduled to instruct. The students are then typically divided evenly between the two LSOs. The instruction technique used in the CQ phase is referred to as "waving." Historically, this term dates back to War World II, when LSOs used big paddles in their hands to communicate with the pilots landing aboard the earliest aircraft carriers.

LSOs are responsible for ensuring each student has the potential to succeed at CQ. The LSO does all of his or her evaluation from the ground by carefully observing, correcting and grading every landing the student makes throughout the CQ phase.

Once an LSO is scheduled to wave a group of students, the LSO continues to wave the group until the CQ phase is complete. This ensures consistency between the student and LSO by building familiarity with each other. This is important in order to increase confidence between LSOs and students. For example, when the student hears certain voice inflections on the radio from his or her designated LSO, the student knows how much power to add or subtract based on the previous CQ events.

5. Solo Flights

"Solo" events require the student to pilot the jet without an instructor (albeit some solo flights still require a lead instructor). Often these events are flown as formation flights with an instructor lead. As a student gains experience and proficiency in each phase of flight they will often end with a check ride followed by a solo flight. The check ride is flown by a senior instructor, designated by an "X" on the FIST. The senior instructor ensures the student has the necessary skill in stage as well as ensuring the student is "safe for solo."

6. Additional Scheduling Constraints

SKEDSOs must adhere to many other constraints when building the daily flight schedule. (Commander Training Air Wing One, [COMTRAWINGONE] &, Commander Training Air Wing Two [COMTRAWINGTWO], 2013). These constraints include (but are not limited to):

- Lead aircraft requirements
- Lead instructor requirements
- Multi-student requirements

- Student crew day limits (12-hour continuous duty)
- Instructor crew day limits
- Instructor event limits
- Student event limits
- Students scheduled no more than six consecutive days
- Instructor and student available periods
- Night events
- Weather constraints
- Student solo and instructor crosswind limits

D. RESEARCH GOALS

Our goal is to enhance the current planning process by alleviating many of the tedious tasks faced by SKEDSOs through an automated optimization program. This, in turn, may allow the SKEDSO to devote more time to manage the time-critical changes. To this end, this thesis has developed and computationally implemented FTS, a mixed-integer, linear, mathematical optimization model. FTS can help determine optimum daily flight schedules for TW-2's Phase II students. A typical instance of this problem consists of approximately 30 students, 65 flight events and 35 instructor pilots. FTS can also improve student throughput by optimizing scheduled events for up to a week, as opposed to a single day.

II. FTS PLANNING MODEL

A. LITERATURE REVIEW

Flight scheduling has been a study subject for many decades. The challenge is how to best utilize limited resources to produce the most efficient schedule. Given student and instructor loading, instructor qualifications, etc., we propose to produce a schedule that maximizes a merit function that rewards early completion of events by students.

Honour (1975) describes many of the constraints that are still present in today's scheduling problem at TW-2. The graphical technique used to solve the problem varies greatly from the formal mathematical optimization model developed in this thesis; however, the description of the problem is nearly identical. Honour uses "edges" to represent student-instructor pairs and does not allow these edges to conflict with each other. He can produce a "reasonable" schedule that does not necessarily maximize student throughput.

Honour also describes the manpower required to produce the daily flight schedule. The similarity between his description almost four decades ago and ours is striking. Today, use of civilian contractor support to build a daily flight schedule frees up the Navy's limited instructors to fly more events, an obvious advantage. An unforeseen disadvantage is that these contractors lack the experience of flying the scheduled events during the execution of the daily flight schedule. Instructors who double as SKEDSOs gain experience flying with each student and first-hand knowledge on student performance. This enables instructor SKEDSOs to pair struggling students with stronger instructors. In addition, instructors also get to know the strengths and weaknesses of their peers and their individual instruction techniques. Some students will respond to differently to various instructor techniques, which in the end will produce better pairings.

An analysis of current flight scheduling practices was done by a group of executive master's in business administration students from Naval Postgraduate School (Hall et al., 2011). The project report details the same flight scheduling problem;

however, this data analysis is mostly concerned with time-to-train criteria in primary flight training. Methods to reduce time to train are recommended, such as reducing the required amount of student “warm-up” events (described later in this thesis).

The daily flight schedule is not unique to training squadrons. The tools and analytical process that is detailed in this thesis can be applied on scheduling problems in the fleet replacement squadrons. A capstone project details scheduling issues in Helicopter Sea Combat Squadron Three (Berry & Tooheny, 2013). The project focuses on areas where increased resources may help reduce student time to train. In addition, changes in syllabus flow are recommended.

Bertsekas (2000) describes job-scheduling problems that consider the ordering of tasks, including prerequisites, in order to complete a construction project in the minimum amount of time. The construction is complete as soon as all the jobs are finished. This differs from the goal of our scheduling process in that some students complete as new students arrive.

Scheduling problems are often difficult to model due to imperfect knowledge of the future. In practice, FTS must check to ensure that each student has met an event’s prerequisites prior to scheduling. However, as opposed to other scheduling problems, we do not know exactly which students will be eligible for which events. The SKESDO must be prepared for unexpected cancelations or student failed events. The complete rebuild of the daily flight schedule may not be desired. Instead, the SKEDSO usually desires to keep the changes to the existing schedule to a minimum. The practice of using a penalty function to encourage persistence is often employed, as described by Brown et al. (1997) and Pinedo (2010, pp. 69–86, 469–490, 552–553).

Pinedo (and references therein) describes the differences between algorithmic- and knowledge-based approaches to scheduling problems. The advantages of each approach are discussed in detail (p. 469). Scheduling at TW-2 has characteristics that lend themselves to an algorithmic approach:

- The high number of events (jobs);
- Real-time changes must be taken into account;

- Scheduling rules are well defined; and
- A mathematical formulation can be developed.

A limitation of the algorithmic approach to our FTS model is the presence of randomness in the environment. The daily flight schedule does account for the risk that any event scheduled may not be completed. As explained in Section I.B, this requires rescheduling of the event in the future and affects related events, which relied on the assumption that the student would complete the event as originally scheduled. Since FTS does not explicitly account for uncertainty, SKEDSO's interpretation of FTS schedules will be necessary.

B. BUILDING THE FLIGHT TRAINING SCHEDULER MODEL

The FTS model utilizes a linear, mixed-integer optimization program that maximizes the value of student events scheduled in a given planning horizon. FTS event values are increased as the student moves forward in the strike training syllabus. This incentivizes the solution to push students through the syllabus. Additional value is also given to events that are completed sooner in the planning horizon. This also incentivizes the FTS model to schedule student events toward the beginning of the planning horizon. The assigned event values are critical to the FTS model and can be set by the SKEDSO, adding a large degree of flexibility.

1. Model Data

Table 2 shows a sample of typical event input.

Event
NFR4101
NFR4102
NFR4201
CQ
AN4301
AN4401

Table 2. Sample list of events

A sample of the instructor and student input data is provided in Table 3.

Instructor
LCDR AK
MAJ AM
LT AJ
CDR BC
LT BD
MAJ BN
LT B, M.

Student
ENS GB
ENS LA
LTJG IC
ENS HC
1st Lt MM
ENS FB
ENS RL

Table 3. Sample list of instructors (left) and students (right)

The planning horizon of the FTS model can be customized by the user. In our testing, we use seven days. Earlier we mentioned that each day is divided into cycles. We model these cycles as “periods.” Each period is equal to approximately three hours. This differs from actual SKEDSO planning. The SKEDSO has five-minute launch windows that may be used to schedule each event. The granularity of the model is limited to just six periods per day in order to reduce the FTS model size. These limited periods make the output less detailed than what will be used in actual practice. That is, the SKEDSO will have to manually enter the launch windows within each period. Periods are labeled “1” through “42.” Table 4 shows a sample mapping of periods to days, where a “1” indicates the day corresponding to each period.

Periods \ Days	D1	D2	D3
P1	1		
P2	1		
P3	1		
P4	1		
P5	1		
P6	1		
P7		1	
P8		1	
P9		1	
P10		1	
P11		1	
P12		1	
P13			1
P14			1

Table 4. Sample mapping periods to days

A sample of instructors who can instruct a given event is found in the FIST (Table 1). If the instructor has any of the following attributes he or she may instruct the event: "Q," qualified; "X," checker; "L," lead; "S," standardization pilot; "D," designated. The SKEDSO must carefully check the FIST each day to ensure the individual instructor is both qualified to instruct the event and that the qualification has not expired. FTS captures FIST data to determine if a given instructor is qualified to instruct an event (see Table 5) and to lead an event (not shown).

	NFR4101	NFR4102	NFR4201	AN4301	AN4401	AN4402	AN4501	AN4601	AN4602
LCDR AK				1	1	1	1	1	1
MAJ AM	1	1	1	1	1	1	1	1	1
LT AJ	1	1	1	1	1	1	1	1	1
CDR BC	1	1	1	1	1	1	1	1	1
LT BD	1	1	1	1	1	1	1	1	1
MAJ BN	1	1	1	1	1	1	1	1	1
LT B, M.	1	1	1	1	1	1	1	1	1

Table 5. Sample instructor event qualification data

Instructors who can instruct CQ events are also entered in a data table (see Table 6).

CQ Instructor
LCDR AK
MAJ AM
LT AJ
CDR BC

Table 6. Sample CQ-qualified instructors

Scheduling for the CQ phase adds additional constraints. The SKEDSO must ensure students start the phase with a firm completion date in place. This date corresponds to the day the students will arrive at the carrier. Other reasons why CQ events differ from other event types include the following:

- The CQ event in the FTS model represents 14 different and distinct flights. In all other event types an event is a single flight.
- The CQ event must be instructed by the same instructor once instruction has begun. Substitution is not allowed.
- A CQ-qualified instructor may instruct up to eight students per event period.
- CQ events are scheduled around aircraft carrier availability.

We have discussed CQ events and how these events differ from other events. In order to account for the aircraft carrier availability the FTS model requires the dates the CQ phase will start. The "hook-down" date is used to determine when to start the CQ phase. The hook-down date is the first day the aircraft carrier can accept a CQ student for his or her first attempted landing at sea. Students who are eligible for the CQ phase will need to start CQ 10 working days ahead of the planned hook-down date. The SKEDSO will need to enter the number of days until the first CQ event. We call this parameter "day to begin CQ," and it is inputted using a miscellaneous data sheet.

There are three possible cases relating the CQ "hook down" date and the FTS planning horizon. The first case is if CQ does not take place within the FTS planning horizon. In this case the user enters a very large number for "day to begin CQ" to signal FTS not to schedule any CQ events. The second case is if CQ begins within the planning horizon. Hence the SKEDSO simply enters the number of days until CQ starts as the "day to begin CQ" parameter. The third case is if CQ is ongoing and will continue (and possibly finish) within the planning horizon. The SKEDSO will enter "1" for "day to begin CQ" and enters the number of days CQ will continue to take place within the planning cycle for the "days in CQ" parameter. FTS then uses this SKEDSO's input to build CQ-eligible days and periods (which we will refer to as CQ-period pairs).

The list of students who are eligible for CQ is also entered as a table for the FTS model. Table 7 is an example.

CQ eligible SNA's
ENS GB
ENS LA
LTJG IC
ENS HC
1st Lt MM
ENS FB

Table 7. Sample CQ eligible students

All events used by the FTS model, with the exception of a few first events in Phase II, have a precedence relationship. These relationships are inputted via a separate data table. Table 8 shows which events are a prerequisite for the event in each column header. A "1" indicates that the event in the left-hand column is a prerequisite for the event on the top of each column.

	NFR4101	NFR4102	NFR4201	CQ	AN4301	AN4401	AN4402	AN4501	AN4601
NFR4101		1							
NFR4102			1						
NFR4201				1					
CQ									
AN4301						1			
AN4401							1		
AN4402								1	
AN4501									1

Table 8. Sample prerequisite mapping

As we see in Table 8, “NFR4101” and “AN4301” do not have prerequisites because either one can be used as the first event within the phase.

As the student progresses through the advanced strike syllabus the SKEDSO must generate a daily "snapshot" of events for which the student is eligible (Table 9). Again, a “1” indicates that the student may be scheduled for the corresponding event. Notice that a student may be eligible for more than one first event.

	NFR4101	NFR4102	NFR4201	CQ	AN4401	AN4402	AN4501	AN4601	AN4602
ENS GB									
ENS LA	1								
LTJG IC	1								
ENS HC				1					
1st Lt MM				1					
ENS FB				1					
ENS RL				1					
2nd Lt GR					1				
ENS YY					1				
ENS DH				1					
ENS FL				1					
LTJG UM									1
LTJG PK									
ENS HG									
ENS CC	1							1	

Table 9. Sample possible first events for each student

The SKEDSO’s tracking process must account for every completed event. The FTS model accounts for previously completed events via tabled data. Table 10 is an example of completed events that may be inputted into the FTS model. A “1” denotes that the event has been completed by the corresponding student. (Note that the abovementioned first events for a student can be derived directly from the table of completed events.)

	NFR4101	NFR4102	NFR4201	CQ	AN4401	AN4402	AN4501	AN4601	AN4602
ENS GB	1	1	1	1	1	1	1	1	1
ENS LA	1	1	1	1	1	1	1	1	1
LTJG IC	1	1	1	1	1	1	1	1	1
ENS HC	1	1	1						
1st Lt MM	1	1	1						
ENS FB	1	1	1						
ENS RL	1	1	1						
2nd Lt GR	1	1	1	1	1				

Table 10. Sample completed events

The advanced strike syllabus includes formation flights and flights where the student must learn to fly the jet in tandem with another aircraft. These multi-plane flights require that an instructor leads the flight. Table 11 is an example.

Event
NFR4101
NFR4102
NFR4201
STK4101
STK4102
STK4103

Table 11. Sample events that require an instructor lead

Events that require a second student with an instructor lead (hence a three-plane event) are entered into the model in the same way as lead events. Likewise, FTS uses a simple table to input solo flights (see Table 12).

Event
NFR4201
CQ
AN4601
AN4602
STK4201
STK4202

Table 12. Sample student solo events

Throughout the planning process there are times that certain instructors are anticipated not to be available due to leave, temporary assigned duty requirements, family emergencies, etc. The FTS model must account for these unavailable periods. Table 13 is an example, where a "1" denotes that the instructor is not available during the corresponding period.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
LCDR AK	1									
MAJ AM	1									
LT AJ	1	1	1	1	1					
CDR BC										
LT BD						1				
MAJ BN										
LT B, M.						1	1	1		

Table 13. Sample instructor unavailability

In most cases, the period and day to begin scheduling each student will be day one. However, in some cases (such as a new class of students), this will not be the case. Table 14 is an example where we tell FTS that three students are not to be scheduled until the seventh period (which corresponds with day 2, per Table 4).

Student	Start period
ENS GB	1
ENS LA	1
LTJG IC	1
ENS HC	1
1st Lt MM	1
ENS FB	1
ENS RL	1
2nd Lt GR	7
ENS YY	7
ENS DH	7

Table 14. Sample student start period

The maximum amount of flights in any period may not exceed the number of jets available, which is given to FTS as part of miscellaneous data.

The FTS model uses event values from the SKEDSO. To ensure that events are given higher rewards for completion earlier in the planning horizon, the following formula is used:

$$r_{ep} = v_e / \sqrt{d_p}$$

where r_{ep} is the reward for event e in period p, v_e is the value for event e, and d_p is the day corresponding to period p. For example, an earlier student event such as "AN4402" can be assigned a value of 3, and a later-stage event such as "BFM4801" can be assigned a value of 7. This signals that scheduling "AN4402" on day one is approximately as valuable as scheduling "BFM4801" on day five or six, but much less valuable than scheduling "BFM4801" on days one through four. Dividing by the square root of d_p ensures FTS builds schedules that place higher rewards on earlier days, while still considers longer-term scheduling effects. Even though our testing uses the above expression to calculate rewards, this is a user-defined function, and a scheduler could enter reward values r_{ep} using any other criteria.

C. FORMULATION

This section introduces the mathematical formulation of the FTS model using a mixed integer program.

1. Indices and Sets

$e \in E$	Student events, e.g., E={form21,CQ...}
$i \in I$	Instructors
$s \in S$	Students
$d \in D$	Days, e.g., D={D1, D2,..D7} (ordered set)
$p \in P$	Periods, e.g., P={p1, p2,..p42} (ordered set)

2. Sub Sets

$P_d \subset P$	Periods in day d (ordered subset)
$I_e^L \subset I$	Instructors who can lead event e
$I_e \subset I$	Instructors who can instruct event e
$I^{\mathrm{CQ}} \subset I$	Instructors who are LSOs and can instruct CQ
$R \subset E \times E$	$(e',e) \in R$ if event e' preceeds event e
$F_s \subset E$	Possible first events for student s
$C_s \subset E$	Already-completed events for student s
$E^{\mathrm{L}} \subset E$	Events which need a lead
$E^{\mathrm{SOLO}} \subset E$	Events which do not need an instructor
$E^3 \subset E^{\mathrm{L}}$	Events which require three planes
$D^{\mathrm{CQ}} \subset D$	Days when CQ takes place, if any
$P^{\mathrm{CQ}} \subset P$	Periods when CQ takes place. $p \in P^{\mathrm{CQ}}$ if $\exists d \mid d \in D^{\mathrm{CQ}}$ and $p \in P^{\mathrm{CQ}}$
$S^{\mathrm{CQ}} \subset S$	Students ready and required to CQ when CQ starts (or currently engaged in CQ)
$\tilde{P} \subset P \times P$	Pairs of periods on the same day in which CQ takes place
$P_i^{\mathrm{NO}} \subset P$	Periods where instructor i is not avaiable

3. Data

v_e	Value for a student completing event e
r_{ep}	Reward to have a student in event e in period p.
	Calculated as $r_{ep} = v_e / \sqrt{d}$, where $p \in P_d$
d_s^0	First day when student s is available
p_s^0	First period when student s is available
M_p	Maximum number of flights in period p
d^{togoCQ}	Number of days students who have started CQ will be in CQ
$d^{\mathrm{tobeginCQ}}$	Number of days until CQ starts
$p^{\mathrm{tobeginCQ}}$	First period in day $d^{\mathrm{tobeginCQ}}$ that CQ starts.
	Calculated as $p^{\mathrm{tobeginCQ}} = \min_{p \in P}\{p \mid p \in P_{d^{tobeginCQ}}\}$

4. Decision Variables

X_{sep}	1 if student s is scheduled for event e in period p
Y_{iep}	1 if instructor i flies event e in period p
L_{iep}	1 if instructor i leads event e in period p
W_{ip}	1 if instructor i waves CQ in period p
$\overline{W}_{id}$	1 if instructor i waves any event e on day d

5. Formulation

$$\max \quad \sum_{s} \sum_{p \geq p_s^o} \sum_{e \notin C_s} r_{ep} X_{sep} \tag{1}$$

subject to:

$$\mathrm{X}_{sep} \leq \sum_{p' < p} X_{se'p'} \ \ \forall s, e, e', p \mid (e', e) \in R, p \geq p_s^o, e \notin C_s \cup F_s \tag{2}$$

$$\sum_{p \in P_d} \sum_{e \mid e \notin E^{\mathrm{SOLO}}} Y_{iep} + \sum_{p \in P_d} \sum_{e \mid e \in E^{\mathrm{L}}} L_{iep} + \sum_{p \in P_d \cap P^{\mathrm{CQ}}} W_{ip} \leq 2 \ \forall i, d \mid i \in I^{\mathrm{CQ}} \tag{3}$$

$$\sum_{p \in P_d} \sum_{e \mid e \notin E^{\mathrm{SOLO}}} Y_{iep} + \sum_{p \in P_d} \sum_{e \mid e \in E^{\mathrm{L}}} L_{iep} \leq 2 \ \forall i, d \mid i \notin I^{\mathrm{CQ}} \tag{4}$$

$$\sum_{p \geq p_s^o} X_{sep} \leq 1 \ \forall s, e \mid e \notin C_s, e \notin \text{"CQ"} \tag{5}$$

$$\sum_{e \notin C_s} \sum_{p \in P_d \mid p \geq p_s^0} X_{sep} \leq 2 \ \forall s, d \geq d_s^0 \tag{6}$$

$$\sum_{s, e \mid p \geq p_s^o, e \notin C_s} X_{sep} + \sum_{e \in E^L, i \in I_e^L} L_{iep} \leq M_p \ \ \forall p \tag{7}$$

$$\sum_{s \mid p \geq p_s^o, e \notin C_s} X_{sep} = \sum_{i \mid i \in I_e^{\mathrm{L}}} L_{iep} \quad \forall \mathrm{e} \in E^{\mathrm{L}} \setminus E^3, p \tag{8}$$

$$\sum_{s \mid p \geq p_s^o, e \notin C_s} X_{sep} = 2 \sum_{i \mid i \in I_e^L} L_{iep} \quad \forall \mathrm{e} \in E^3, \mathrm{p} \tag{9}$$

$$\sum_{s \mid p \geq p_s^o, e \notin C_s} X_{sep} = \sum_{i \mid i \in I_e} Y_{iep} \quad \forall \mathrm{e}, p \mid e \notin E^{\mathrm{SOLO}} \tag{10}$$

$$\sum_{s|p \geq p_s^o, e \notin C_s} X_{sep} \leq 8 \sum_{i|i \in I^{\text{LSO}}} W_{iep} \quad \forall e, p | e = \text{"CQ"}, p \in P^{\text{CQ}} \tag{11}$$

$$\sum_{e|i \in I_e} Y_{iep} + \sum_{e|i \in I_e^{\text{L}}} L_{iep} + \sum_{e \in E^{\text{CQ}}} W_{iep} \leq 1 \quad \forall i, p \,|\, i \in I^{\text{CQ}}, p \in P^{\text{CQ}} \tag{12}$$

$$\sum_{e|i \in I_e} Y_{iep} + \sum_{e|i \in I_e^{\text{L}}} L_{iep} \leq 1 \quad \forall i, p \,|\, i \notin I^{\text{CQ}} \tag{13}$$

$$\sum_{e \notin C_s} X_{sep} \leq 1 \quad \forall s, p \,|\, p \geq p_s^o \tag{14}$$

$$L_{iep} + \overline{W}_{id} \leq 1 \;\; \forall d \in D^{CQ}, p \in P_d, i \in I^{\text{CQ}}, e \notin E^{\text{L}} \tag{15}$$

$$Y_{iep} + \overline{W}_{id} \leq 1 \;\; \forall d \in D^{CQ}, p \in P_d, i \in I^{\text{CQ}}, e \notin E^{\text{SOLO}} \tag{16}$$

$$\overline{W}_{id} \geq W_{iep} \quad \forall i \in I^{\text{CQ}}, d \in D^{CQ}, p \in P_d, e = \text{"CQ"} \tag{17}$$

$$\overline{W}_{id'} = \overline{W}_{id} \quad \forall i \in I^{\text{CQ}}, d, d' \in D^{\text{CQ}} \tag{18}$$

$$\sum_{p \in P_d} X_{sep} = 2 \;\; \forall d \in D^{\text{CQ}}, s \in S^{\text{CQ}}, e = \text{"CQ"} \tag{19}$$

$$\sum_{p \in P_d} X_{sep} = \sum_{p \in P_{d'}} X_{sep} \;\; \forall d' \in D^{\text{CQ}}, d = d^{\text{tobeginCQ}}, s \in S^{\text{CQ}}, e = \text{"CQ"} \tag{20}$$

$$X_{sep} = X_{sep'} \quad \forall (p, p') \in \tilde{P} \;\; , s, e = \text{"CQ"} \tag{21}$$

$$Y_{iep} = 0 \;\; \forall i, p \in P_i^{\text{NO}}, e \tag{22}$$

$$L_{iep} = 0 \;\; \forall i, p \in P_i^{\text{NO}}, e \tag{23}$$

$$W_{iep} = 0 \;\; \forall i \in I^{CQ}, d \in D^{CQ} p \in P_i^{\text{NO}} \cap P_d, e = \text{"}CQ\text{"} \tag{24}$$

$$X_{sep},\; Y_{iep},\; L_{iep},\; W_{ip},\; \overline{W}_{id} \in \{0,1\} \;\forall s, i, e, p \tag{25}$$

Equation (1) is the objective function for the FTS model. The objective is to maximize the total reward of all the student events flown.

Equation (2) builds our precedence constraints. The FTS model uses these constraints to ensure that student events are flown in the required sequence.

Equations (3) and (4) build the instructor daily flight limits. The FTS model limits the number of total instructor events to a maximum of two. For instructors who are LSOs, FTS limits the combination of instruction flights, lead flights and LSO duties to two. For all other instructors the combination of lead and instructor flights cannot exceed two.

Equation (5) builds constraints that limit each student to flying each event that has yet to be completed only once. The notable exception to this constraint is we omit any event that is a CQ event. The FTS model uses one "macro" CQ event to schedule every CQ eligible student for multiple CQ events throughout the entire CQ training phase. This modeling "work-around" allows the FTS model to closely mirror current CQ scheduling that is used by TW-2 without involving a detailed modeling of the intricate scheduling nuances related to CQ.

Equation (6) limits up to two events per day for every student. The FTS model uses equation (7) to account for the limited number of jets available in each period. This number is a bound on the amount of student events flown, X_{sep}, plus the amount of lead instructor events flown, L_{iep}. There is no need to account for instructor events, Y_{iep}, because these instructors are in the same jet as the student.

Equations (8) and (9) are used to schedule a lead instructor with each event so required. We need to use two equations because there are two- and three-plane events. The equality constraints enforce the schedule of the exact number of students, instructors and leads, which is a requirement for these multi-plane events.

Equation (10) is used to schedule instructors for instructional flights. For every non-solo flight we ensure that a qualified instructor is scheduled.

For CQ events, LSOs are permitted to wave up to eight students. This is not in conflict with equation (10), because CQ is a solo event (thus, equation (10) does not apply here). Equation (11) builds the constraints for all students in CQ.

Equations (12)-(14) all serve to keep from scheduling multiple events for students and instructors within the same period. Equation (12) is used by the model to ensure squadron LSOs are scheduled for either one instructor event, one lead event or one CQ event per period. Note this constraint does not limit the LSO from instructing up to eight students. It works in tandem with equation (11) for that purpose. Equation (13) builds similar constraints for all other instructors. These instructors may only instruct one event or lead one event in each period. Equation (14) prevents any student from executing more than one event in any one period.

When any LSO is scheduled to wave students during the CQ phase we desire the model to ensure that this instructor continues to wave. It could definitely be the case that there are other (more valuable) events for which these instructors can be scheduled; however, we want to ensure that the LSO continues to wave and does not fly in other events due to the limited availability of aircraft carriers. Accordingly, equation (15) builds the constraint ensures all LSOs are not scheduled to wave and lead in the same day. Equation (16) ensures all LSOs are not scheduled to wave and instruct in the same day. Equation (17) is used by FTS to ensure that if any instructor is scheduled to wave, he or she does so for the entire duration of the CQ.

Equation (18) ensures that once a group of students is waved by an LSO, the same LSO continues to wave these students.

Since CQ is a single event in the FTS model we need to ensure that it is scheduled twice each day. Equation (19) ensures that each student scheduled for CQ does two CQ events each day. Additionally students in CQ are not permitted to fly any event that is not CQ (CNATRA, 2013). To build these constraints the FTS uses equation (20).

To account for the specific timing of CQ periods FTS builds CQ event-period pairs in equation (21). These pairs constrain the FTS model by ensuring that CQ events take place in consecutive periods. For example if in the first period of the day a CQ event takes place, then another CQ event is also flown in the second period of the day.

Equations (22), (23) and (24) build constraints for instructor unavailable periods.

Equation (25) establishes decision variable domains.

D. IMPLEMENTATION

The FTS model has been implemented in the General Algebraic Modeling System (GAMS) utilizing GAMS/CPLEX (GAMS, 2014) as the solver engine. With a typical, real-world, Phase II student loading the FTS model has approximately 150,000 binary variables and 30,000 constraints. It takes approximately 15 minutes to attain a solution within 15 percent from optimal, and three hours to reduce that gap under five percent. Testing and implantation are further discussed in the next chapter.

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III. TESTING AND VALIDATION

This chapter describes the testing and validation performed for the FTS model. Model results are discussed and compared to current scheduling practices. The reader should be cautioned that FTS has not been validated for all aspects of Phase II scheduling. A list of additional functionality that would further validate the model is discussed in Chapter IV. As currently configured, FTS could be used as a proof-of-concept and substantial time-saving optimization tool. FTS may also be used to solve related scheduling problems, such as the Navy's primary flight training squadrons. Testing in this chapter demonstrates all the current capabilities of the FTS model.

A. UNIT TESTING

During the development of FTS, model testing has been conducted to verify functionality of newly added constraints and data interaction. The tests check the basic building blocks of the model and their interactions with other separate blocks. Table 15 describes each test, its expected output and the test result.

Test Number	Test Configuration		Expected Output	Test Result
	Test Goal	Test Setup		
1	Verify single-plane student-instructor events are scheduled	Input single-plane event, a student in need of the event and a qualified instructor	Student and instructor scheduled to complete event	Pass
2	Verify test 1 is scheduled in first available period	Same input as test 1 with period 1 available	Student-instructor pair are scheduled to complete event in period 1	Pass
3	Verify higher priority single-plane student-instructor events are scheduled first	Input student 1 in need of an event with a higher priority than student 2 with only 1 qualified instructor	Student 1 scheduled prior to student 2	Pass
4	Verify event precedence	Input a partial Phase II syllabus with a student and a fully qualified instructor	Student-instructor pair should be scheduled in accordance with syllabus flow	Pass

Test Number	Test Configuration		Expected Output	Test Result
	Test Goal	Test Setup		
5	Verify students and instructors are scheduled for at most one event per period	Same input as test 4 with added events	Students and instructors are scheduled for one event per period	Pass
6	Verify students are not scheduled for more than two events per day	Same input as test 5	Students are scheduled for two events per day maximum	Pass
7	Verify instructor is not scheduled for more than two events per day	Same input as test 5 with two students	Instructor is only scheduled for two events per day	Pass
8	Verify no unnecessary idle time	Same input as test 5	Students are scheduled in the first two periods of each day	Pass
9	Verify instructors are only scheduled for events they are qualified to instruct	Same input as test 6 with one fully-qualified instructor and an instructor only qualified in “AN” type events	Instructor only qualified in “AN” type events is not scheduled for any other events	Pass
10	Verify student solo events are scheduled	Same input as test 7 with student solo events	Students are scheduled for solo events without instructors	Pass
11	Verify two different student-instructor pairs can be scheduled in the same period	Same input as test 10	Multiple student instructor pairs are scheduled in first available period	Pass
12	Verify only qualified lead instructors are scheduled as flight leads	Same input as test 11 with two-plane events	Only qualified lead instructors are scheduled to lead events	Pass
13	Verify student events that require a lead aircraft with an instructor are properly scheduled	Same input as test 11 with two-plane events	Each two-plane student event has a lead aircraft with a qualified lead instructor and a student instructor pair	Pass

Test Number	Test Configuration		Expected Output	Test Result
	Test Goal	Test Setup		
14	Verify two-plane solo events are scheduled with an instructor lead and solo student	Same input as test 13 with two-plane student solo events	Students are scheduled with an instructor lead	Pass
15	Verify three-plane events requiring two student-instructor pairs and one lead instructor are properly scheduled	Same input as test 14 with three-plane events	Each student three-plane event has a lead aircraft with a qualified lead instructor and two student-instructor pairs	Pass
16	Verify student three-plane solo events are scheduled with an instructor lead and solo students	Same input as test 15 with three-plane student solo events	Two student-solos events are scheduled with an instructor lead	Pass
17	Verify CQ events are scheduled with only qualified LSOs	Same input as test 16 with CQ events and qualified LSOs	LSO is scheduled with student CQ solo events	Pass
18	Verify each LSO can wave up to eight students	Same input as test 17 with 10 CQ eligible students	Two LSOs are scheduled for the CQ events and each LSO waves no more than eight students	Pass
19	Verify once an LSO is assigned to CQ he continues to be scheduled for the remaining CQ events	Same input as test 18	The same LSOs are used in every CQ event	Pass
20	Verify CQ events start on scheduled day	Same input as test 19 with a user-entered CQ start and end date	CQ events begin on user-entered date	Pass
21	Verify CQ events terminate on scheduled day	Same input as test 20	CQ events terminate on user-entered date	Pass
22	Verify students and instructors are not scheduled when not available	Same input as test 20 with unavailable time periods entered	Student and instructors are scheduled only when available	Pass
23	Verify maximum amount of jets available per period is not exceeded	Same input as test 20 with only one jet available	No two- or three-plane events are scheduled	Pass

Test Number	Test Configuration		Expected Output	Test Result
	Test Goal	Test Setup		
24	Verify model runs entire strike training syllabus, instructors and students	Same input as test 23 with full syllabus, all students and instructors	A full, seven-day schedule (feasible solution)	**Pass**
25	Verify model runs Phase II strike training syllabus in less than 30 minutes	Same input as test 24 allowing up to 30 minutes of runtime	A full seven day schedule (optimal solution)	**Unable**

Table 15. Testing results

Worth further discussion is test 25. The 30-minute time constraint does not suffice to attain optimality. The solution produced is guaranteed to be within 15 percent from optimal. We discuss its value to SKEDSOs in the next sections.

B. FTS MODEL OUTPUT

The FTS model outputs a seven-day schedule assigning events, students and instructors to periods. Table 16 is an example of FTS output. The first period of scheduled events is listed. The scenario assumes CQ is currently ongoing. “TAC4301,” a tactical formation flight, and “BFM4101,” a basic fighter maneuvers fight, are two-plane events that require an instructor and a lead. “BFM4701,” another basic fighter maneuver flight, is a solo student event.

Day	Period	Students	/	Instructor				
Monday	0800-1100							
	Event							
	LSO/Leads							
	CQ	VITAL	LENIN	HOP	CRAT	ROSE	ABE	VILLIAN
	LTHOSER							
	TAC4301	YOUNG	/	LCDRCAL				
	MAJBEN							
	BFM4101	IENDERSOI	/	CAPTDALT				
	LCDRBLUTO							
	BFM4701	SWIFT						
	LTDYSON							

Table 16. Sample FTS output

C. FTS OUTPUT COMPARISON

An important check for validating FTS is to confirm its output mirrors closely to what current SKEDSOs are producing. This check has been done with actual data during a Naval Air Station Kingsville site visit, December 2–6, 2013, and implemented with VT-22. CNATRA publishes on its website the daily flight schedule once the OPSO and the squadron commanding officer signs as the final approval authority. For these dates, corresponding to the site visit, the FTS model output yields many of the same student events. It should be noted that some of these student events are flown by different qualified instructors, but in most cases this is due to instructor swaps (i.e., alternative solutions of the same quality).

FTS produces a daily schedule in 30 minutes (versus 16 SKEDSO-hours). This reduction may lower manpower costs for the Navy. Additionally, when entire schedules are canceled for any reason, FTS can rapidly respond with a new daily schedule, which accounts for these lost events. Note: the new schedule needs not match the canceled one because, for example, student or instructor availability may not be the same.

Additionally, FTS is considering the effects of the current day's schedule on future daily schedules. That is, its output is responsive and sensitive to longer-term scheduling goals.

D. FTS INEFFICIENCIES

As previously discussed, the mixed-integer characteristic of the FTS model requires a large amount of time in order to attain an optimal solution. In practice, and as a tool to assist the SKEDSO, we recommend FTS run for 30 minutes and outputs a (possibly suboptimal) schedule. This schedule may still save the SKEDSOs hours in planning and allow them to focus on capturing the data that FTS has yet to incorporate, as discussed in Chapter IV.

The optimality gap can be reduced by letting FTS execute for a longer time. For example, in our scenario, a schedule can be guaranteed to be within five percent from optimal in approximately three hours. SKEDSOs, however, may prefer the 15 percent gap solution in 30 minutes, for two reasons:

(1) This schedule differs only slightly from the one guaranteed to be five percent optimal; that is, the improvement to the actual solution is negligible, and the gap reduction is due to improvements on the upper bound.

(2) Squadrons are scheduling 80–100 flights a day with an approximate 20 percent incompletion rate. Thus, in a 15-hour flight day, a three-hour period could reasonably have two to three incomplete events. If these events are assumed to be complete during the execution of FTS, its output will need to be revised.

IV. FUTURE WORK

The FTS model has been tested on actual squadron data. On-site verification and testing evidenced the need for additional functionality that was incorporated into FTS after the visit. Functionality that was not added but may be desired prior to field use of the FTS model will be discussed in this chapter.

A. CREW REST

Crew rest is a constraint that applies to students and instructors. An instructor crew day cannot exceed 12 hours. After the last scheduled event of the day the instructor requires 10 hours, off-duty time following the last scheduled event or briefing (COMTRAWINGTWO, 2013). Student crew rest criteria are even more restrictive.

The FTS model currently does not coordinate periods to time. The periods in the model were previously described as corresponding to event cycles. The length of event cycles vary throughout the day, however, for modeling purposes, it could be assumed to be a constant 2.5 hours, or the shortest cycle of the day. This would enable additional constraints limiting the periods that instructor and students may be scheduled given a previous day's schedule.

B. LECTURES

Phases throughout the strike fighter training syllabus are often preceded by a lecture. These lectures must be scheduled and are a required part of the syllabus flow that the FTS model ignores. The lectures could be incorporated into the model by adding them as an event with their corresponding constraints. The lectures have additional constraints to which the SKEDSO must adhere and that flight events do not possess. The lecture for a phase cannot be given on the same day as the first event in the phase. The student must be given time to assimilate the information learned in the lecture for at least one night.

C. NIGHT EVENTS

Night events must obviously be scheduled during nighttime hours. FTS periods could technically comprise any hour of the day, so the last two periods may be assumed to be night periods, and limiting night events to them would capture this requirement. However, that would also require additional constraints to ensure all other events are scheduled during daytime periods.

D. CROSS-COUNTRY EVENTS COMPLETED EN-ROUTE TO DETACHMENTS

Squadrons often save events to be used for detachments. Instead of just flying a jet from home base to a detachment location, squadrons attempt to make use of this required flight time by incorporating training during the transit. It is obviously more efficient to conduct student events en-route to detachment locations. Which events will be saved and for which student becomes a complex problem in itself. However, a decision to delay training in anticipation that the student will conduct these events on a detachment is something that we may reasonably incorporate into a multi-day optimization model like FTS.

E. STUDENT WARM-UP WINDOW

If a student does not fly for seven consecutive days he or she becomes eligible for an optional warm-up (CNATRA, 2010, pp. I-15). If the student does not fly for 14 consecutive days he or she must be scheduled for a warm-up event. In addition to these two constraints, there are various constraints within each training phase dictating when warm-up events must be scheduled. The FTS model as described in this work completely ignores this requirement.

An additional constraint: $\sum_{p \geq p_s^o, e} X_{sep} \leq 1 \; \forall s$, would ensure each student is scheduled at least once in a seven day period on the first day FTS is run. However, on day two, FTS would run again and any student event that was scheduled to meet this constraint on the first day could be rescheduled in a later period. Here is where a persistence method (Brown et al. 1997) could be employed, which would favor the originally scheduled day one event thus keeping the student out of the optional warm up window.

F. OUT-AND-IN EVENTS

Often student events are scheduled as “out-and-in” events. These events are simple to schedule and allow the SKEDSO to use the same instructor student pair for consecutive events. The pair will use a jet, fly the first event and land at an outlying field. Then they will debrief and brief the next flight at the outlying field. Finally, the pair will takeoff and execute the second event landing back at home field.

The out-and-in practice has the benefit of reduced travel time to and from airspace where the training is conducted. Obviously, less transit time yields more time and fuel for conducting each event’s required maneuvers. The current FTS does not schedule out-and-in events. However, we note that a close example modeled by FTS is CQ events. FTS models CQ conservatively with respect to the actual resources: One group of students will fly the jets and execute their first CQ event, while a second group of students drive to the outlying field. After the first group lands the second group of students then use the same jets to fly their CQ event. Two more jet-student swaps are conducted with the group of students that drove to the outlying field flying the jets back to home field and other group of students drive back to home field. Conducting CQ in this manner allows squadrons to minimize the use of jets in CQ. The FTS model currently schedules the CQ events correctly but it over-commits jets to these events. Thus, in practice, the squadron has more jets available to utilize than the FTS model reports.

G. TRAINING INTEGRATION MANAGEMENT SYSTEM INTEROPERABILITY

If the FTS model is to be used on a regular basis, a data script needs to be written and tested for bringing the data in from TW-2’s flight data system, training integration management system (TIMS). The data tables used in this thesis have been built manually.

It would be highly desirable (and less prone for error) if this process were automated. All the data needed exists in the TIMS database and in squadron-maintained spreadsheet files.

H. EFFICIENCY IMPROVEMENTS

FTS could benefit from decomposition techniques or reformulations, which may improve solving time. With the increased efficiency gained, it may be possible to include the entire strike training syllabus rather than just Phase II. Incorporating Phase I into the optimization process, which includes the same resources as Phase II with additional students, would yield a more efficient and complete daily flight schedule.

V. CONCLUSION

This thesis has developed FTS, a mixed-integer, linear, mathematical optimization model that addresses the need for a fast, automated scheduling tool, capable of producing quality-measurable solutions. FTS-built schedules provide a SKEDSO with a template they may use to produce a complete schedule with only minor manual modifications, such as a few needed substitute events.

Producing the daily flight schedule is a complex and tedious process that is reliant on a high level of expertise. Using FTS has three main benefits:

1. FTS produces a daily schedule in 30 minutes versus 16 SKEDSO-hours. A reduction in the time to produce the daily schedule may lower manpower costs for the Navy. Additionally, when entire schedules are canceled for any reason, FTS can rapidly respond with a new daily schedule, which accounts for these lost events.
2. FTS produces a seven-day schedule versus one-day schedule, allowing FTS to anticipate future event requirements. Since FTS is considering the effects of the current-day's schedule on future daily schedules the output are more efficient. FTS ensures that students meet time critical gates by accelerating their training and accelerating other students to train as pairs.
3. FTS allows the SKEDSO to place a value-oriented metric on the total events scheduled. This gives SKEDSOs an objective, quantitative measure for comparison among different schedules, and the ability to assess the impact of event cancelations or substitutions.

FTS test runs with actual data produced schedules that closely resembled those produced by SKEDSOs (a one-day schedule). The SKEDSO may scan the FTS schedules for days two through seven for time critical events, for example, to ensure students they desire meet specific gates: the SKEDSO may build a requirement into FTS to reschedule the current day's canceled event.

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