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AN AID FOR FLIGHT SQUADRON SCHEDULING

by

Tetsuichi Kawakami

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An Aid for Flight Squadron Scheduling

by

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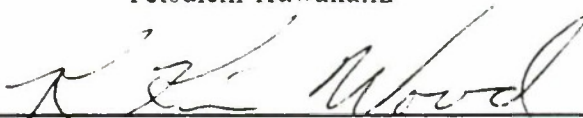
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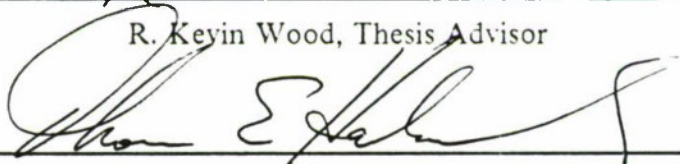


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## ABSTRACT

An integer programming approach is taken to schedule daily training flights in a Japanese operational flight squadron and an American flight training squadron.

Two related models for the Japan Maritime Self-Defense Force (JMSDF) are considered for pilots just out of the training pipeline and for fully qualified pilots. Explicit measures of effectiveness that update pilot currency are used, while instructor and aircraft availabilities create resource restrictions. The models are implemented in the GAMS language and solved with the ZOOM solver, using simulated data which include up to 19 pilots. A typical model with 477 constraints and 129 variables is solved in 2.30 seconds on an IBM 3033AP.

In addition, a training squadron model in the United States Marine Corps is considered. The approach is similar to the JMSDF models, except that a student must be assigned an instructor and there is a difference in training policy. The model is formulated using GAMS and solved with the ZOOM solver, using the data from the training squadron HMT 303, Camp Pendleton, CA. The data includes 11 student pilots and 15 instructors. A typical model with 146 constraints and 984 variables is solved in 23.5 seconds on an IBM 3033AP.

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### THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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## I. INTRODUCTION

A military flight squadron carries on many different activities such as mission flights, training flights, maintenance, meetings, etc. In order to carry on these activities effectively, scheduling officers must match, on a daily basis, personnel and other resources to the activities. This is a complex task since there are many policies and resource limitations which must be considered. For instance, training flights must satisfy requirements of a training syllabus, limits on daily flight hours are mandated for pilots and crewmen, and pilots cannot fly unless aircraft are available.

Currently, most squadron scheduling is done with pencil and paper and it is not unusual for schedulers to be struggling with tomorrow's schedule well past normal working hours today. Comparing two tentative schedules is difficult since no objective criteria for the efficiency of a schedule have been established. It is the purpose of this thesis to develop prototypic mathematical programming models which include objective measures of schedule efficiency and which simplify and partially automate the daily scheduling process.

There are many different types of flight squadrons in various military services and various countries. Many of these squadrons have different scheduling needs and it would be impossible to model all the differing requirements. Consequently this thesis limits its scope to training flights in an anti-submarine helicopter squadron of the Japan Maritime Self-Defense Force (JMSDF), with which the author has significant experience, and to the scheduling of a United States Marine Corps (USMC) helicopter training squadron, for which data is readily available.

### A. FLIGHT SCHEDULING

#### 1. In an Operational Squadron

A *flight* is an aircraft proceeding on a mission. The flights in an operational flight squadron can be categorized as (a) actual mission flights, such as search and rescue, (b) aircraft tests (or functional checks) and (c) pilot and crew training. Actual mission flights and test flights may be scheduled or unscheduled (on request), while training flights are always executed by schedule. The difficult part in flight scheduling is to decide if a candidate *training flight* has priority over other training flights, and to choose a set of training flights for the squadron which does not conflict with resource restrictions such as those imposed by aircraft and instructor availability. The flight

activities in an operational squadron of the JMSDF and the difficulties in training flight scheduling are briefly described below.

Scheduled mission flights are usually conducted periodically, and on a rotating basis. A mission flight is assigned to a qualified *team*, which is a special crew whose members are semi-permanent for the purposes of coordination and consistency. Typically, the number of teams in a squadron is less than 20. Scheduled aircraft test flights are required after periodic maintenance which is performed at an interval of several hundred flight hours for each aircraft. Specially qualified pilots and aircrewmembers are necessary for these test flights, and the scheduler can arbitrarily assign those available pilots and aircrewmembers who have the "testing" qualifications.

Unscheduled mission and unscheduled test flights are sometimes required. For an urgent mission flight requirement, schedulers usually assign a *ready* team which is waiting on alert condition. For an urgent test request from the maintenance division, schedulers keep some qualified test crew in reserve and assign that crew if necessary.

In view of the above discussion, it can be seen that scheduling teams for missions or scheduling members of a crew for test flights is not a very difficult problem. Thus, the focus of this thesis is on scheduling training flights. Training is controlled by pilots' or aircrewmembers' syllabi. In the JMSDF, a syllabus consists of various *items*, which are particular procedures such as a "Single Engine Landing" or "TACAN approach" performed in flight. Each item in a syllabus must be repeated periodically to maintain or update currency. One training flight may then consist of several items from a syllabus. To schedule training flights, schedulers must consider the priority of individual training, and pick several pilots with their respective syllabus items and make sure of the availability of aircraft and instructors.

## 2. In a Training Squadron

Scheduling in a training squadron in the USMC involves different problems than those described above. The squadron's mission is to train pilots to a specific level of proficiency and to send these pilots on to operational squadrons by specified dates. Student pilots usually arrive in groups which results in an uneven workload for the squadron and its schedulers. Also, the amount of time allowed for completion of training can vary from student to student by the requirement of an operational squadron. Scheduling is further complicated by the need to assign specific instructors for specific training flights because not all instructors are qualified to instruct all items.

A syllabus *item* of the training squadron in the USMC corresponds to a *flight* itself. The training flights (or items) proceed step by step through several syllabus

categories. Once an item is completed, it is never repeated and the student moves on to the next set of allowable items, depending on partial precedence relations between items.

For both the JMSDF and USMC squadrons, the manual method, using pencil and paper, takes excessive time and the results are, in many cases, far from optimal. In fact, no measure of effectiveness (MOE) is even used in evaluating alternative schedules. Therefore, it is the purpose of this thesis to formulate and solve objective scheduling models with explicit MOEs.

## **B. TIME HORIZON OF THE SCHEDULE**

In scheduling daily training flights, a scheduling period of a week to a month would be desirable. With this scheduling period, upcoming resource limitations and possible unavailability of pilots could be worked around. However, this leads to two problems: forecasting resource limitations and forecasting pilot availability. In most cases, this data is only known for a few days in advance. Furthermore, multi-day scheduling models may be computationally intractable. Thus, the focus of this model will be on models which schedule only one day at a time.

Multi-day schedules can be generated from such daily models by solving for the first day of a period, updating data under the assumption that the first day's schedule is carried out, solving for the second day, updating the data and so forth. Long range strategies, taking into account the upcoming unavailability of a pilot, for example, can be introduced into such a process by modifying pilot priorities. In this case, some interaction between the solver and a human scheduler would be necessary.

## **C. RELATED MODELS**

### **1. Event Scheduling at NATC**

Davis [Ref. 1] presents a data management system and heuristic algorithm for solving a flight scheduling problem at the Naval Air Test Center (NATC). The U.S. Navy Test Pilot School (TPS) at NATC provides pilots and flight engineers the skills to conduct flight testing. The TPS must manage various types of aircraft and instructors along with the trainees. Much of the database management problem deals with updating the status of personnel information such as syllabus progress and flight hours. While this is an important problem, it is technically easy and it is not the purpose of this thesis to create a complete scheduling system. Consequently, database management will only be addressed peripherally.

On the other hand, Davis' work in developing an algorithm to schedule daily *events*, i.e., training flights, is directly related to the methods developed in this thesis.

This thesis effectively creates more rigorous integer programming formulations with explicit MOEs for problems which Davis attacks with a heuristic algorithm lacking an MOE.

## **2. Combat Aircraft Scheduling**

Phillips [Ref. 2] presents a computerized mission flight scheduling system for combat aircraft. His problem may be stated: "Given a set of mission requests covering a 24 hour period, how should these requests be assigned to combat aircraft?" The mission flights have attributes such as priority, type of aircraft specified, aircraft quantity, start time, duration and possibly a request for a particular squadron. Also, aircraft status records are reported for each squadron specifying the number of flyable aircraft of each type. Given the collected mission requests and the aircraft data, Phillips' algorithm assigns mission flights to aircraft as follows:

1. Order mission requests by aircraft type, priority and start time,
2. Order aircraft records by aircraft type and squadron. Squadrons are specified on a rotating basis; however, a mission that needs two or more aircraft is assigned to a single squadron,
3. For the first mission request, assign the first aircraft satisfying feasibility requirements based on aircraft type and availability, if possible,
4. Iterate the procedure until all missions are assigned or all available aircraft are assigned,
5. Resolve conflicts with the aid of a human operator.

While this kind of algorithm could be applied to a training environment, it is clear that the algorithm is only a heuristic and has no explicit MOE. Thus, this approach will not be pursued here.

## **3. Airline Crew Scheduling Model**

Some scheduling problems have been solved with set partitioning models. In principle, a set partitioning model says, "Job requirements must be covered by an appropriate work force." For example, the airline crew scheduling problem has been attacked by set partitioning model for years [Ref. 3 , 4]. An airline flight schedule is fixed for a certain period of time, (e.g., a month or a week.) by marketing efforts. Thus, the number of flights, departure and arrival times, and the respective airports are given. Crew scheduling is then carried out to satisfy the crew requirements for these flights.

An airline crew reports to a home airport and starts a series of flights following the current schedule. The schedule usually tries to minimize crew costs, while

1. Covering every flight over the time horizon exactly once with an appropriate crew,

2. Assuring briefing and de-briefing time between flights,
3. Allowing rest periods after certain lengths of duty periods,
4. Allowing for overnight rest and stops away from the originating airport, if appropriate, and
5. Limiting the number of days spent away from the home airport.

Set partitioning methodology works by first generating all, or a "good" subset of, potential individual crew schedules, called *pairings*. Pairings consist of collections of flight requirements (routes) or *legs* which must be covered by a crew. The best collection of pairings is then determined using an integer programming model.

The formulation of the set partitioning model is as follows. Let  $i$  correspond to flight legs which must be covered, and let elements  $j \in J_k$  correspond to candidate pairings for crew  $k$ . Then,  $A_{ij} = 1$  if pairing  $j$  satisfies requirement  $i$ ; otherwise,  $A_{ij} = 0$ . The decision variable  $X_j = 1$  if pairing  $j$  is selected; otherwise,  $X_j = 0$ . Let  $C_j$  be the cost of pairing  $j$ . The integer program is then,

$$\begin{aligned} \text{Minimize} \quad & \sum_{j=1}^n C_j X_j \\ \text{subject to} \quad & \sum_{j \in J_k} X_j = 1 && \text{for } k = 1, 2, \dots, c, \\ & \sum_j A_{ij} X_j = 1 && \text{for } i = 1, 2, \dots, m, \\ & X_j \in \{ 0, 1 \} && \text{for } j = 1, 2, \dots, n. \end{aligned}$$

The set partitioning approach allows complicated constraints on the scheduling of a crew to be placed into the model generator instead of the integer program. Great flexibility in modeling results from this.

An approach similar to set partitioning could be taken with training flight scheduling. The advantage of this technique would be the ability to look over a time horizon greater than one day and to take into account upcoming resource or pilot availabilities. The disadvantages are that a very complicated generator would be required, an extensive, long-range database would be necessary and general constraints (non-set partitioning constraints), such as maximum flight hours over all aircraft, would be necessary. Consequently, this approach is not examined here but it is suggested that future research investigate this topic.

#### D. THESIS OUTLINE

Taking the integer programming approach, simplified models are considered. All the activities other than flights such as meetings, maintenance, duty officers and other events on ground are considered only indirectly in the models, i.e., only the training flight schedule will be modeled. Also, only pilots will be scheduled; scheduling aircrewmen is left for a future effort. Aircraft availability, such as a number of flights and the total flight hours goal of a squadron, will be dealt with as a given resource.

In Chapter II, the background for flight scheduling and the criteria used for modeling both the JMSDF and USMC flight scheduling problems are discussed. Chapter III presents two separate mathematical models for a JMSDF operational squadron, in which two different pilot qualifications are considered. A mathematical formulation for a training squadron in the USMC is also presented.

All the models are implemented in the GAMS language. The GAMS formulations are listed in Appendices A, B, C and D. Data for the JMSDF anti-submarine squadron model is artificially generated data. The USMC training squadron model was solved using actual data from the helicopter training squadron HMT 303 at Camp Pendleton, CA. The results of the computational tests are discussed in Chapter IV.

## II. BACKGROUND FOR FLIGHT TRAINING SCHEDULING

This chapter considers criteria for and regulations affecting training scheduling in an anti-submarine helicopter squadron in the JMSDF and in a helicopter training squadron in the USMC.

### A. AN OPERATIONAL HELICOPTER SQUADRON IN JAPAN

#### 1. A Squadron

Specifically considered is anti-submarine helicopter squadron HS 101 in the JMSDF, in which the author served for four years. This squadron flies HSS-2B anti-submarine helicopters which have almost the same airframe and features as the SH-3H aircraft carrier based anti-submarine helicopter used in the U.S. Navy (USN). The aircraft has four crew stations, two side-by-side pilot seats up front and two sensor operator seats in the back.

Pilots, aircrewmembers and aircraft are the major resources in the flight squadron to be scheduled. In addition, resources such as ammunition supplies, availability of air space (range), maximum traffic in the airfield, and the number of maintenance teams may affect a schedule.

Most of the training regulations for this squadron are stated in the document named "*HSS-2(A,B) Kunren Jisshi Hyoujun*" (in Japanese) [Ref. 5], in which the training enforcement standards for HSS-2(A,B) aircraft are described. The rest of the section A of this chapter is devoted to an introduction of the basic concepts of flight training in a Japanese squadron.

#### 2. Readiness

An operational flight squadron must be ready for missions that are, or may be required of it. The objective of the scheduling officer is to maximize the readiness of the squadron. In other words, combat readiness should be the MOE of an operational flight squadron. To keep the readiness level high, those who work in a squadron need to engage in various activities including flight training. In the JMSDF, readiness is defined in terms of the team, not the readiness of individual pilots or aircrewmembers. However a modified criterion of pilot combat readiness is necessary, since we are dealing with individual pilot training rather than team training. The modified criteria will be discussed in section 8 of this chapter.

### 3. Pilots

It is necessary to have both a "pilot in command" and a "co-pilot" to operate multipiloted aircraft like the HSS-2B. The definitions of pilot qualifications are borrowed from a USN document as a general concept for multipiloted aircraft [Ref. 6 : p. 1-7, p. 12-3]. "Pilot in command" is defined as "The pilot assigned responsibility for safe and orderly conduct of the flight." He usually acts as a "first pilot," which means "an individual positioned with access to the flight controls and is exercising principal active control of the aircraft." On the other hand, the co-pilot is "assisting the (first) pilot" and "is immediately ready to operate the flight controls." Therefore, his major task is to assist the pilot in command. Hereafter the term *aircraft commander* is used to mean a pilot who has the qualification needed to be assigned as a pilot in command and a pilot who does not have this qualification is called a *second pilot*. The term "pilot in command" and "co-pilot" will be used as a role designation for a particular flight, rather than a qualification.

### 4. A Pilot's Tour

If a pilot has just graduated from a training squadron, which means that he is on his first tour, he has the basic background to begin working as a second pilot; it takes at least 18 months for him to become an aircraft commander. If a pilot has sufficient experience, which means that he is in his second or third tour, he usually becomes qualified as an aircraft commander right after refresher training. Once he is qualified, he must maintain his proficiency and will be checked annually.

### 5. Syllabus

Training requirements consist of a number of items collected into a syllabus. An excerpt of a syllabus for an aircraft commander is given in Table 1. (The actual table would cover 12 months and 23 items.) Each *item* corresponds to a certain in-flight procedure and has a code name for identification. For example, B2221D means "normal landing procedure in daytime," while B2221N means "normal landing procedure at nighttime." Thus, a *flight* is performed with a collection of items in the JMSDF syllabus. In Table 1, the category "Basic" means basic flight procedures, and consists of items such as "ASE off landing", "Autorotation", etc. There are other categories such as "Instrument" which means instrument flight procedures such as "Ground Controlled Approach (GCA)", and categories such as "Tactics" which consists of tactical maneuver training like "SONAR dipping and approach", etc. "Time" is the listed standard time in hours required to complete the training procedure. The columns on the right side of Table 1 correspond to the months since a pilot started the syllabus. An "F" in the box

in one of these columns indicates that the training flight should be flown during the month, either to maintain currency or as part of the training process to become an aircraft commander. In practice, any items from the previous month which were not completed would be added onto the set of items for the following month.

There are two types of flight training syllabi, one for an aircraft commander and one for a second pilot. Both syllabi have some common items because the purpose of training is mainly to provide better control skills and emergency procedure execution, which are the same requirements whatever the pilot qualification is.

A second pilot performs his duties to assist a pilot in command while flying and also takes the flight controls when he performs some syllabus training under the supervision of a pilot in command. For a second pilot, training is more thorough to ensure coverage of the many cases that may have to be dealt with in the future as a pilot in command. It is necessary to assign an instructor to complete a second pilot syllabus item, although non-syllabus flights can be flown with a pilot who does not have instructor qualification.

An aircraft commander is assumed to be able to do everything that is necessary to fly with safety. He does not have to fly with an instructor to do his syllabus training. He is also assumed to know his weak point(s) and should be able to modify his training to take this into account, if necessary.

Table 1. AIRCRAFT COMMANDER SYLLABUS MATRIX (HSS-2B, EXCERPT)

Item Code	Category	Training Item	Time (hours)	Month				
				1	2	3	4	5
B2221D	Basic	Normal Landing, Day	0.2	F		F	F	
B2221N		Normal Landing, Night	0.2	F	F		F	F
B2222D		ASE off Landing, Day	0.2		F			F
B2222N		ASE off Landing, Night	0.2			F		

*a. Second Pilot Syllabus*

For a second pilot, there is a special 18 month program to qualify as an aircraft commander. The program has 39 kinds of flight training items, each of which must be repeated within a particular time interval according to the second pilot syllabus matrix. In the first 12 months, the second pilot works in the left-side seat in the cockpit as a co-pilot with an instructor acting as aircraft commander. In the remaining six months, he sits in the right-side seat, which is the aircraft commander's seat, under the supervision of the designated instructor.

*b. Aircraft Commander Syllabus*

Once a second pilot has been qualified as an aircraft commander, he is required to maintain his currency, which is checked annually. He can fly and perform training items as a pilot in command and does not need an instructor to complete any syllabus items. The syllabus for a pilot in command contains 23 training items, each of which must be repeated according to the syllabus matrix over the period of a year. (See Table 1.)

**6. Day and Night Training**

Some training items are categorized as daytime training and some as nighttime training because visibility is limited at night and repetitive training is needed to complete a mission safely at night. Daytime flights can be scheduled on any day unless special events are scheduled for the squadron. Night flights cannot be scheduled every night since these are essentially overtime work and there is some environmental concern for noise.

**7. Aircraft Availability**

The number of aircraft available or the number of flight hours available to use those aircraft are important resource restrictions. It is assumed that on a single day, a pilot in training will use a single aircraft for his training flight. The same aircraft can be used in consecutive flights for other pilots if it has enough hours remaining to be flown until the next inspection is due to be performed. In this case, the number of available aircraft cannot be used directly to represent a restriction in aircraft availability. In fact, the number of available aircraft and the number of flight hours can be approximated as the number of *hops* available, which means the total number of flights in a time period (day). Thus, the number of pilots flying is limited to the number of available hops.

The number of available hops on a day is related to the maintenance schedule, and is effectively dictated by the maintenance officer. He does not usually permit the

use of every aircraft that is in flyable condition. He specifies which aircraft and how many hops are available for flights, and reserves some aircraft for unscheduled missions. He may withhold some aircraft to control flight hours of the aircraft, in order to smooth the maintenance workload on the limited number of maintenance teams.

#### **8. Criteria for Daily Scheduling**

Since no criteria for individual readiness have been developed in the JMSDF, tentative criteria that will work in a scheduling model are necessary. The following describes tentative criteria.

##### *a. Who flies?*

Who should fly tomorrow for training? This is a simple question but the answer is not obvious. Some criteria that exist in the scheduler's mind are as follows:

1. Those who did not fly recently should fly tomorrow, and
2. Those who did not complete any syllabus items recently should be scheduled for tomorrow's flight.

Given every date that each pilot flew is recorded and updated in a database, the difference in days between the date the pilot last flew and tomorrow's date, can be used as a component of a coefficient in the objective function of a scheduling model. As this number becomes larger, the pilot must become more likely to be selected for a training flight.

##### *b. Which item is to be performed?*

Similar to the above, the difference in days between the date a pilot last performed a syllabus item and tomorrow's date can be used as a component of a coefficient in a scheduling model's objective function. The larger the number is, the more likely the pilot should be scheduled to fly the item.

Another factor in any objective function should be the set of available (or required) items for the month (along with any items from the previous month which were not completed). If an item is to be performed once during the month, the value of the factor is one. If the item is not to be performed, its value is zero (and, in fact, the item will not be included in the model at all). Furthermore if an item is to be performed twice during a month, which can occur in the second pilot syllabus, the value of the factor is two.

## 9. Flight Training Regulations

### a. *Minimum Training Requirements*

Certain items of a syllabus may be critical for an aircraft commander because these must be performed in accordance with "the minimum training requirements" which regulate the training interval of the certain items for aircraft commanders. These requirements exist because certain items are considered to be particularly important for safety or are skills essential to complete a mission. These items should have larger weights in the objective function of the model. Such a factor is not included in the second pilot model.

### b. *Maximum Flight Hours*

Safety is one of the biggest concerns in peacetime operations. Pilots must have enough rest and sleep between flight and/or alert duties. A certain amount of time should be guaranteed as rest after a mission or a training flight. For instance, if a night flight had been flown, then the crew does not have to report early next morning. They report late in the morning or at noon, depending on the landing time of the previous night's flight. Another restriction on flight hours is that a pilot will typically be involved in some administrative work on the ground. The amount of time required by this work must be taken into account.

Given the above concerns, a simple method to define the maximum flight hours for each pilot is taken for a daytime schedule. The unavailable hours are evaluated resulting from night flight and/or by routine business on the ground. Then, those unavailable hours are subtracted from the working hours to give the maximum flight hours. For nighttime flying the scheduler will typically require that all flights be completed by a specified time, such as 2200 hours. The maximum flight hours for a pilot will then simply be the amount of time between sunset and 2200 hours.

### c. *Training Pacing*

It is necessary to create an upper limit on the number of items in one training flight for each pilot to establish an appropriate training "pace". A pilot must have a certain number of opportunities to fly in a month for both daytime and nighttime training. It is better to do a few items each time he flies rather than to do all the required items during a single flight, or to do only one item at a time. For modeling purposes it is necessary to introduce a constraint to limit the number of syllabus items per flight that assures some level of training tempo or pace for pilots. If this constraint is too tight, i.e., the limit requires too few items per flight, pilots cannot complete their assigned items

during the assigned time period, i.e., a month. If it is too unrestrictive, the quality of training will be poor.

## **B. A TRAINING SQUADRON IN THE USMC**

### **1. A Squadron**

In the USMC, training squadrons are usually called Fleet Readiness Squadrons (FRSs). The specific squadron that is modeled here is HMT 303 of Camp Pendleton, CA. The squadron has two types of helicopters, UH-1 utility helicopters and AH-1J attack helicopters. The squadron receives trainee pilots called (1) Replacement Aircrews (RACs), who are newly designated aviators, (2) refresher pilots, who have worked outside of the aviation community for a while and (3) transition or conversion pilots, who were pilots of a different type of helicopter or fixed-wing airplane and have been ordered to switch to either the UH-1 or the AH-1J. The mission of the squadron is to give these crews a training course which is called "Combat Capable Training." In this thesis, the Combat Capable Training for RACs flying the AH-1J syllabus is modeled.

RACs have just finished primary flight training when they come to the squadron so that they can immediately begin the Combat Capable Training. It nominally takes 20 weeks for a RAC flying the AH-1J to go through this training. However, the period is often shortened by the requirement of an operational squadron or an amphibious ship deployment schedule. Different sized groups of students are assigned to HMT 303 every few months, so, typically, there are students at various stages of their training in the squadron. The squadron may have busy or slow seasons depending on the number of student pilots currently assigned.

### **2. Readiness**

Combat Capable Training brings a student pilot up to a 60 percent level of the combat readiness percentage (CRP), which is the readiness measure used by the USMC. CRP is defined as "The percentage of a specific tactical aircraft MACCS (Marine Air Command and Control System) syllabus in which personnel are proficient" [Ref. 7 : p. 2-3].

The Combat Capable Training comprises a basic syllabus which is identified by flights numbered between 100 and 199. After completion of the course at the training squadron, the graduates continue training at the operational squadron to obtain a higher CRP, up to 100 percent. The training regulations are described in OPNAVINST 3710.7M, and MCO P3500.14B and P3500.16, which are known as the "Aviation Training and Readiness Manual," or the "T&R manuals" for short. [Ref. 6 , 7 , 8]

CRP might be useful for scheduling purposes in an operational squadron, but in a training squadron, a student's progress is simply measured by the number of syllabus items completed. This is true because the squadron's biggest concern is to send the student pilots, with a guarantee of 60 percent of CRP, to the respective operational squadrons "on schedule." Thus, the scheduling objective should be designed to force every student to be on schedule.

### 3. Syllabus

In the USMC training squadron, every syllabus *item* corresponds to *one training flight*, which takes one to two hours to complete. A student pilot pursues syllabus flights in a fairly flexible order, from aircraft familiarization to tactical training flights. However, prerequisites do force some orderings among items.

#### a. Categories of Syllabus

The syllabus for RACs consists of nine categories, which are Familiarization (FAM 100 to 111), Instruments (INST 120 to 125), Formation (FORM 130 to 132), Terrain flight (TERF 140), Navigation (NAV 150 to 152), Air to Ground (AG 160 to 162), Tactical flight (TAC 170 to 171), Night Vision Goggles (NVG 180 to 182) and Combat capable check (CCX 190). Refreshers, conversion and transition trainees can skip some of the items listed above according to the T&R manual, vol.3. Since the data for refreshers, conversion and transition trainees were not available, modeling efforts for other than RACs are omitted. [Ref. 8]

#### b. Instructors

There are eight instructional qualifications in HMT 303. An instructor may not have all the qualifications. Instructors can only instruct students in the syllabus categories for which they are qualified. The instructional qualifications are defined as follows:

**Flight Leader (FLT LDR):** A pilot who can lead four or more helicopters,

**Division Leader (DIV LDR):** A pilot who can lead up to three helicopters,

**Section Leader (SEC LDR):** A pilot who can lead another helicopter, i.e., a pilot who can lead a formation (The first three categories are concerned with formation training. At least one section leader needs to be assigned to one section, i.e., two helicopters),

**NATOPS Instructor (NATOPS INST):** The most experienced pilot in the squadron, or the "standard pilot",

**Assistant NATOPS Instructor (ANI):** Four of the most experienced pilots who assist the NATOPS instructor,

**Instrument Board:** Experienced pilots who can evaluate instrument flight,

**Terrain Flight Instructor (TERF INST):** One of the Weapons and Tactics Instructor qualifications (WTI): It includes three modes of flight; low altitude, contour and nap of the earth,

**Night Vision Goggles Instructor (NVG INST):** The other WTI qualification which is related to special equipment used for night attack.

Instructors are qualified for each category by completing their special syllabus called Instructor Under Training (IUT), and by repeating the syllabus periodically to maintain currency in each category. In the USMC model, only the current qualifications are considered; updating currency for instructors is not modeled.

*c. Prerequisites*

Syllabus flights need not to be scheduled strictly in the order given in the T&R manual, vol.3, but some items do have prerequisites. Any syllabus item can be picked from any category, unless the pilot does not have enough background to perform the item. For example, night introduction (FAM109) is essential to the Night Vision Goggle training (NVG 180-182). Prerequisite relationships and all allowable items at every point of the training progression are listed in Figure 1.

*d. Day and Night Training*

The squadron that is modeled provides only basic combat capability and, consequently there are not many night items in the syllabus. In fact, the nighttime items comprise only five out of 34 total items. Two of these are in the category of FAM, one concerning formation, and the other three are NVG items. NVG items have an additional illumination requirement. That is, a minimum amount of moonlight must be available for safe use of night vision goggles. Thus NVG items can only be flown a few nights during each month.

**4. Other Flight Training Regulations**

*a. Minimum Training Requirements*

The minimum training requirements for Naval aviators are defined in a loose manner in OPNAVINST 3710.7M [Ref. 6 : p. 11-3] (See Table 2.). In addition, there are some stricter regulations in the T&R Manual, vol.1 [Ref. 7 : p. 3-3]. Examples of minimum training requirements in the USMC are listed below:

1. As a minimum goal, pilots should fly 15 to 20 flight hours per month,
2. No pilot shall sign for an aircraft night flight who has not flown that model within the previous 15 days. He must fly a daylight flight first,
3. Minimum peacetime illumination requirement for the use of the NVG's is that illumination sufficient to provide .0012 LUX.



*b. Maximum Flight Hours*

Safety requirements regarding the maximum number of flight hours are described in Figure 2 [Ref. 6 : p. 8-7]. As in the JMSDF, the time spent with administrative duties affects the maximum available hours of instructors. The flight hours of a student pilot are also limited, but this limitation is subsumed by a restriction on the maximum number of items flown in a day, which is two.

1. Rest and sleep :	At least 8 hours every 24 hour period.
2. Continuous Alert and/or Flight Duty :	Less than 18 hours. In the case of excess, 15 hours off duty should be provided.
3. Daily flight time :	Up to 12 hours. Assumes 4 hours of ground time for briefing and debriefing.
4. Weekly Maximum flight time :	Up to 50 hours.
5. Monthly (30 Days) maximum flight time :	100 hours.

Figure 2. Maximum Flight Time for Naval Aviators (OPNAVINST 3710.7M)

*c. Training Effectiveness*

Normally in a training squadron, no more than two flights per day are scheduled for a student pilot. This limitation comes from a training effectiveness concern, as in the JMSDF. Two items per day is considered the maximum given the flight hour constraints and the need to spend considerable time studying before making any flight. Some less capable student pilots may be limited to at most one flight per day.

*d. Flight Hour Goal*

Aircraft availability in a USMC training squadron is seen as a target on the total flight hours on a given day. It is dictated by the maintenance officer to maintain an appropriate operational pace and for smoothing the maintenance schedule. Because it may not be necessary or possible to exactly meet the target, this target should be thought of as a goal to be achieved if possible.

### III. MATHEMATICAL MODELS

Three mathematical models are presented for scheduling training flights in a Japanese operational flight squadron and an American flight training squadron. The first model covers aircraft commanders in a JMSDF helicopter squadron and the second model covers second pilots in the same kind of squadron. The third model is for scheduling trainee pilots in a USMC helicopter training squadron.

The reason that the JMSDF type model was split into two parts is because of the difficulty in combining both aircraft commander and second pilot training in a single training flight. Rank concerns occur; two aircraft commander qualified pilots may be assigned to the same flight; and a second pilot may or may not complete a syllabus item, depending upon whether or not the pilot in command is qualified as an instructor.

If the model is split between aircraft commanders and second pilots, each segment becomes simple, listing priority items which need to be performed for either aircraft commanders or second pilots. However, resource limitations, specifically the number of available hops, should be dealt with in a combined manner. It is assumed that the scheduler has already decided, given that the number of available aircraft is known, how many hops are going to be assigned to aircraft commander training and how many to second pilot training. Although the split models cannot optimally solve the whole scheduling problem, the results should be useful for advisory purposes. Furthermore, multiple runs could be made with modified hop allocations between the two models.

No similar problem arises in the USMC training squadron because all flights are made by a student with an instructor.

#### A. OPERATIONAL SQUADRON, AIRCRAFT COMMANDER MODEL

An operational flight squadron scheduling model for aircraft commanders in the JMSDF is considered first. The purpose of the pilot's training is to maintain his level of currency. An aircraft commander does not need an instructor to complete his syllabus. The problem is "which pilots should be selected for training flights, and which items should be performed during the flights?"

There are three types of indices in this model:  $t$ ,  $p$ , and  $i$ . Index  $t$  represents the current date and is used only to identify data which must be updated daily. Thus, no constraints or summations are expanded by  $t$ . The index  $p$  identifies pilots with the aircraft commander qualification, while  $i$  indexes training items.

The daytime schedule and nighttime schedule are controlled separately because daytime items cannot be executed at night, and vice versa. Consequently, two separate models, a daytime model and a nighttime model are constructed. The index set of nighttime training items is denoted by  $I^N$  and daytime training items is denoted by  $I^D$ .

In addition, the items which a pilot may be assigned to are limited. The standard training items are established in the syllabus matrix which indicates the items that are required to be performed in a particular month, depending on how many months have passed since the last readiness check flight (See Table 1.). By considering which column (or month) a pilot  $p$  is in, a set of indices  $I_{p,t}$  of "allowable" items can be constructed. This set consists of all items listed for the month which the pilot has not completed by the start of day  $t$ , along with any items from previous months which have not been completed. The allowable items for pilot  $p$  on day or night  $t$  is denoted  $I'_{p,t}$ .

Two decision variables are defined in the model, namely  $X_{i,p}$  and  $Y_p$ .  $X_{i,p}$  has value one if pilot  $p$  performs item  $i$ ; otherwise, it is zero.  $Y_p$  is one if pilot  $p$  flies; otherwise, it is zero. It is necessary to define  $Y_p$  to control the interval between two successive training flights for each pilot.

Data that are used in the model are as follows: The maximum flight hours for pilot  $p$ , denoted  $\bar{H}_{p,t}$ , and the training time taken for each item  $h_i$ , are used in a constraint to limit the number of flight hours for each pilot. The maximum training items per day for pilot  $p$  is denoted  $\bar{I}_p$  and is used for limiting the number of items for each flight.  $A_t$  denotes the number of aircraft available on day  $t$  to limit the number of flights. The rest of the data  $W_i$ ,  $D_{i,p,t}$ ,  $\bar{D}_i$ ,  $T_{p,t}$  and  $F_p$  are used in the objective function.

The objective of the model is to select the least trained pilots and their items. Some training items are considered more critical for safety or mission success than others. Additionally, regulations require that if a pilot does not perform some of these critical items during a particular time interval, he will lose his aircraft commander qualification. Thus, priority must be given to those critical items. The weight or importance of item  $i$  is denoted by  $W_i$ , and forms part of the objective function. The three values of  $W_i$  are 2.0 for the very critical items; 1.0 for the critical items; and 0.5 for less critical items. (See Appendix 1.)

The next piece of data appearing in the objective function is the number of days since the last completion of item  $i$  for pilot  $p$ , denoted  $D_{i,p,t}$ . For example, consider two pilots, neither of whom has completed a critical item  $i$  recently. Which pilot should be selected to fly first? Flight records would be examined and the pilot who did the item

earlier, i.e., has the larger value of  $D_{i,p,t}$ , would be assigned a higher priority, since he is closer to losing his qualification than the other.

One thing that needs to be mentioned is that some less critical items occur in the syllabus only once or twice a year. Normalization is necessary over items which are both frequently and not so frequently scheduled. The maximum interval between repetitions of item  $i$ , without losing qualification, is denoted  $\bar{D}_i$ . Then, the value of assigning pilot  $p$  to item  $i$  is linearly related to  $D_{i,p,t} / \bar{D}_i$ , when  $D_{i,p,t} \leq \bar{D}_i$ . For  $D_{i,p,t} > \bar{D}_i$ , pilot  $p$  is in a very undesirable situation and the value is made to vary quadratically in  $D_{i,p,t} / \bar{D}_i$ .

Readiness can be viewed from the point of proficiency and currency [Ref. 7 : p. 3-3]. For the purpose of currency, not only the interval of days between each item should be controlled, but also the interval of days between each flight should be smoothed. The weight of  $Y_p$  in the objective function contains the factor  $T_{p,t}$ , which is the number of days since the last training flight for pilot  $p$ . Another factor  $F_p$  (nominally set to 1) is used to balance the effects of both  $X_{i,p}$  and  $Y_p$  in the objective function.

The basic constraints of the training schedule model require several equations that ensure that no pilot exceeds a maximum number of flight hours  $\bar{H}_p$ , and that the number of available hops is not exceeded. A restriction on maximum flight hours  $\bar{H}_p$  is an obvious necessity for safety reasons and because there are only so many hours in a day. For a daytime schedule,  $\bar{H}_p$  is the difference between the working hours and the "busy" hours on ground, which is the number of potential flyable hours. From limited aircraft availability, the number of pilots flying is limited to the number of available hops  $A_t$ . The schedulers may also enforce a daily limit on the number of training items performed by pilot  $p$ , denoted  $\bar{I}_p$  in order to maintain the quality of each training flight.

The technical description of the model is given below.

### 1. Index Sets

- $t \in T$  current date,
  - $p \in P_t$  pilots (aircraft commanders) available for training on day  $t$ ,
  - $i \in I^N$  nighttime training items,
  - $i \in I^D$  daytime training items,
  - $i \in I_{p,t}$  allowable training items for pilot  $p$  on day  $t$  and
- |                  |                    |  |
|------------------|--------------------|--|
| $i \in I'_{p,t}$ | $I_{p,t} \cap I^N$ | the allowable items for nighttime scheduling, or |
|                  | $I_{p,t} \cap I^D$ | the allowable items for daytime scheduling.      |

## 2. Data

- ×  $\bar{H}_{p,t}$  maximum number of flight hours per day for pilot  $p$ ,
- ×  $h_i$  training time that is needed for item  $i$ ,
- $\bar{I}_p$  maximum number of training items per day for pilot  $p$ ,
- ×  $T_{p,t}$  number of days since the last flight for pilot  $p$ ,
- $F_p$  factor on  $T_p$  to balance flight currency and item currency,
- ×  $W_i$  criticality index (weight) of training item  $i$ ,
- $D_{i,p,t}$  number of days since last performing item  $i$  for pilot  $p$ ,
- ×  $\bar{D}_i$  upper limit on training interval for item  $i$  (days) and
- $A_t$  number of hops available.

## 3. Decision Variables

$$X_{i,p} = \begin{cases} 1 & \text{if pilot } p \text{ performs item } i, \\ 0 & \text{otherwise.} \end{cases}$$

$$Y_p = \begin{cases} 1 & \text{if pilot } p \text{ flies,} \\ 0 & \text{otherwise.} \end{cases}$$

## 4. Formulation

$$\text{Maximize} \quad \sum_{p \in P_t} \sum_{i \in I'_{pt}} C_{i,p,t} X_{i,p} + \sum_{p \in P_t} C_{p,t} Y_p$$

$$\text{Subject to} \quad \sum_{i \in I'_{pt}} h_i X_{i,p} \leq \bar{H}_{p,t} \quad \forall p \in P_t \quad (1)$$

$$\sum_{i \in I'_{pt}} X_{i,p} \leq \bar{I}_p \quad \forall p \in P_t \quad (2)$$

$$\sum_{p \in P_t} Y_p \leq A_t \quad (3)$$

$$X_{i,p} - Y_p \leq 0 \quad \forall p \in P_t, i \in I'_{pt} \quad (4)$$

$$X_{i,p} \in \{0, 1\} \quad \forall i, p$$

$$Y_p \in \{0, 1\} \quad \forall p$$

$$\text{where } C_{i,p,t} = \begin{cases} W_i D_{i,p,t} / \bar{D}_i & \text{if } D_{i,p,t} < \bar{D}_i, \\ W_i (D_{i,p,t} / \bar{D}_i)^2 & \text{if } D_{i,p,t} \geq \bar{D}_i. \end{cases}$$

$$C'_{p,t} = F_p T_{p,t}.$$

Constraints (1) limit the number of flight hours for each pilot during the day. Constraints (2) limit the maximum number of training items for each pilot during the day. Constraint (3) limits the aircraft availability. Constraints (4) imply that a pilot must fly if he performs a syllabus item.

## B. OPERATIONAL SQUADRON, SECOND PILOT MODEL

The indices and the decision variables in the second pilot model are the same as in the first model. However, here,  $p$  indicates second pilots, and  $i$  corresponds to their syllabus items. The data consists of several different components which are described below.

An instructor is an essential resource used to complete a second pilot syllabus item. It is assumed that if a second pilot performs more than one item, the same instructor will teach for all items. Furthermore, it is assumed that an instructor will not be assigned to more than one second pilot during a day. Thus, the number of second pilots performing training items on any day is limited by the number of instructors available, and the number of hops available.

A fundamental difference from the aircraft commander model is that there is no weight of criticality  $W_i$  of items, which is designed to avoid losing the aircraft commander qualification. Instead, the situation requires that a second pilot must dedicate himself to completing his syllabus to become an aircraft commander on schedule. Delay from the original schedule often occurs for second pilots. Delay is recognized by schedulers in a subjective fashion but can be quantified. For example, a second pilot is supposed to perform a set of items in column  $m$  in the syllabus matrix, but he may not have done well enough to proceed to column  $m$  since many items may not have been successfully completed in column  $m-1$ . In this case, his delay  $k$  is one month. In order to recover from the delay,  $DL_p$  is defined as a relative delay from the original training term. For instance, if the delay is  $k$  months and the whole training term lasts 18 months, then  $DL_p = (18 + k)/18$ . The factor  $DL_p$  gives higher priority to a second pilot  $p$  who is behind schedule.

As mentioned previously, a particular item in a second pilot syllabus may have to be performed more than once in a given month. A higher priority should be assigned to an item if it must be repeated during a month. In order to achieve such a priority system, the data element  $M_{i,p,t}$  is introduced.  $M_{i,p,t}$  denotes the number of times  $i$  must be performed during the current month. If  $M_{i,p,t-1} = k$  when  $k > 1$ , and item  $i$  is performed on day  $t - 1$ , then  $M_{i,p,t} = k - 1$ , and the priority for item  $i$  is reduced.

The formulation of the second pilot model follows.

### 1. Index Sets

- $t \in T$  current date,
- $p \in P'$  pilots (second pilots) available for training on day  $t$ ,
- $i \in I^N$  nighttime training items,
- $i \in I^D$  daytime training items,
- $i \in I_{p,t}$  allowable training items for pilot  $p$  on day  $t$  and
- $i \in I'_{p,t}$ 
  - $I_{p,t} \cap I^N$  the allowable items for nighttime scheduling, or
  - $I_{p,t} \cap I^D$  the allowable items for daytime scheduling.

### 2. Data

- $DL_p$  weight of training importance (delay from the "schedule"),
- $M_{i,p,t}$  number of training requirements on item  $i$  for pilot  $p$  in this month,
- $D_{i,p,t}$  number of days since last performing item  $i$  for pilot  $p$ ,
- $\bar{D}_i$  upper limit of training interval for item  $i$  (days),
- $T_{p,t}$  number of days since the last flight for pilot  $p$ ,
- $F_p$  factor on  $T_p$  to balance two objective function terms,
- $\bar{H}_{p,t}$  maximum flight hours per day for pilot  $p$ ,
- $h_i$  flight hours needed for item  $i$ ,
- $\bar{I}_p$  maximum training items per day for pilot  $p$ ,
- $J_t$  number of available instructors and
- $A_t$  number of available hops.

### 3. Decision Variables

- $X_{i,p} = \begin{cases} 1 & \text{if pilot } p \text{ performs item } i, \\ 0 & \text{otherwise.} \end{cases}$
- $Y_p = \begin{cases} 1 & \text{if pilot } p \text{ flies,} \\ 0 & \text{otherwise.} \end{cases}$

#### 4. Formulation

$$\text{Maximize} \quad \sum_{p \in P'_t} \sum_{i \in I'_{pt}} C_{i,pt} X_{i,p} + \sum_{p \in P'_t} C'_{p,t} Y_p$$

$$\text{Subject to} \quad \sum_{i \in I'_{pt}} h_i X_{i,p} \leq \bar{H}_{p,t} \quad \forall p \in P'_t \quad (5)$$

$$\sum_{i \in I'_{pt}} X_{i,p} \leq \bar{I}_p \quad \forall p \in P'_t \quad (6)$$

$$\sum_{p \in P'_t} Y_p \leq \min\{ J_t, A_t \} \quad (7)$$

$$X_{i,p} - Y_p \leq 0 \quad i \in I'_{pt}, \forall p \in P'_t \quad (8)$$

$$X_{i,p} \in \{0, 1\} \quad \forall i, p$$

$$Y_p \in \{0, 1\} \quad \forall p$$

$$\text{where } C_{i,pt} = \begin{cases} DL_p M_{i,pt} D_{i,pt} / \bar{D}_i & \text{if } D_{i,pt} < \bar{D}_i, \\ DL_p M_{i,pt} (D_{i,pt} / \bar{D}_i)^2 & \text{if } D_{i,pt} \geq \bar{D}_i. \end{cases}$$

$$C'_{p,t} = F_p T_{p,t}.$$

Constraints (5) limit the flight hours for each pilot during the day. Constraints (6) limit the maximum number of training items for each pilot during the day. Constraint (7) limits the number of hops resulting from instructor and aircraft availability. Constraints (8) imply that one must fly if one performs a syllabus item.

#### C. MARINE CORPS TRAINING SQUADRON, TRAINEE MODEL

The overall daily scheduling problem for a training squadron is considerably simpler than the corresponding problem for an operational squadron. For instance, an operational squadron must consider actual missions, aircraft tests and training while a training squadron is not concerned with actual missions. Nonetheless an interesting and useful integer program arises from the training scheduling problem.

On a given day, any student pilot in training has a set of allowable training items which can be flown. These items may include all training flights remaining for qualification or some subset of these since certain training items may have prerequisite items not yet flown. The basic scheduling problem then consists of assigning available pilots to allowable training items while meeting constraints on the availability of aircraft and instructors, maximum number of items and flight hours for the student and possibly several side constraints.

There are four index types in this case: again, the index  $t$  just indicates the current date and is used on data which must be updated every day;  $i$  is a syllabus item but here also means one flight (or hop);  $p$  is a student pilot; and  $q$  is an instructor.

The definitions of the variables are a bit different from the JMSDF models. There are three binary variables, two general integer variables, and two continuous non-negative variables. One of the binary variables is again  $X_{i,p}$ , which is one if a student  $p$  performs an item  $i$ ; otherwise, it is zero. The next variable  $Y_{i,p,q}$ , takes the value one if instructor  $q$  teaches student  $p$  for item  $i$ ; otherwise, it is zero. The third binary variable  $W_p$ , is used to reduce the value of a second flight (or item) in a day. Formation training requires a pair of aircraft and a pair of pilots. Therefore, the number of formation flights must be even. The two integer variables  $V$  and  $V'$  indicate the number of pairs of formation items scheduled for daytime and nighttime respectively. The two continuous variables, denoted  $Z^+$  and  $Z^-$ , represent either a positive or negative deviation from a flight hours goal for the squadron.

The objective of the problem is to keep students "on schedule." A student is on schedule if at the current point in time  $t$  the number of training items completed equals the number of items which should have been achieved. While such a desired level or "goal" is not defined in the training guidelines, we can approximate such a value as

$$\hat{N}_{p,t} = N_p \frac{D_{p,t}}{D_p},$$

where  $\hat{N}_{p,t}$  = number of items which should have been completed by day  $t$  for pilot  $p$ ,  
 $N_p$  = total number of syllabus items in the course for pilot  $p$ ,  
 $D_p$  = total number of days that pilot  $p$  is allowed for training and  
 $D_{p,t}$  = number of days that a pilot has been assigned to the training squadron.

So, if training nominally takes place over a period of 140 days (20 weeks) and requires a total of 30 items and a particular pilot has been in the squadron for 100 days, the goal for training items completed is

$$\hat{N}_{p,t} = \frac{30 \times 100}{140} = 21.4.$$

Letting  $N_{p,t}$  denote the actual number of items completed by pilot  $p$  up to but not including day  $t$ , the value of assigning pilot  $p$  to item  $i$  will be defined as

$$C_{p,t}^1 = (1 + [\max \{ 0, \hat{N}_{p,t} - N_{p,t} \}]^2).$$

Thus, the value of assigning a pilot to item  $i$  increases quadratically with underachievement of the completed items goal.

The upper limit of the number of flights per student pilot is set to two in the model. That is, a second flight for a student pilot could be scheduled on the same day  $t$ . In this case, the value of assigning pilot  $p$  to the second item should be

$$C_{p,t}^2 = (1 + [\max \{ 0, \hat{N}_{p,t} - (N_{p,t} + 1) \}]^2).$$

Rather than expanding the formulation by defining  $X_{i,p}^1$  and  $X_{i,p}^2$  in an obvious manner, a binary variable  $W_p$  is defined which is one if a pilot is assigned to two flights during the day. This variable has objective function coefficient  $C'_{p,t} = C_{p,t}^2 - C_{p,t}^1$ .

The constraints of the USMC model are significantly more complicated than in either of the JMSDF models. Below is described the relationships enforced by the constraints. First, every item which is flown by a student must be paired up with a qualified instructor. The number of flight hours for an instructor on a given day is limited as is the total number of items flown by a student pilot (The maximum is one or two depending on the student.)

If an item has more than one prerequisite remaining for a student then that item cannot be performed. However, if only one item  $i$  is the only unfinished prerequisite for an item  $i'$ , then item  $i'$  is allowable but can only be flown if item  $i$  is also flown.

The value of a second flight during a day for a particular pilot may be less than the value of the first flight. Also, since all formation flights are performed with pairs of students only an even number of daytime or nighttime items can be performed. Finally, any schedule should attempt to hit the flight hours goal set by maintenance.

For formation training, not only the number of formation flights must be even, but also a pilot must not be paired with himself in a formation. The former requirement must be constrained separately for daytime and nighttime, using the integer variables  $V$  and  $V'$ . There are three items which are involved with the formation category; two of them are daytime items and the other is a nighttime item. The corresponding set of formation items is denoted  $I_F^D$ , and  $I_F^N$  respectively. For night formation flights, no student will be paired up with himself since there is only one nighttime formation item FORM132. For daytime formation training, a possible way to handle the problem is to limit the number of formation training per a student pilot to one. i.e.,

$$X_{i_p} + X_{i'_p} \leq 1 \quad \forall p, \text{ where } i = \text{FORM130}, i' = \text{FORM131}.$$

A similar method can be taken to eliminate the possibility of pairing an instructor with himself in a formation, by limiting the number of formation instructions to one:

$$\sum_{p \in P_t} \sum_{i \in I_F^D} Y_{i_p q} \leq 1 \quad \forall q, \text{ where } I_F^D = \{ \text{FORM130}, \text{FORM131} \}.$$

Another method would be to use a strict prerequisite relationship between formation items such as FOM-130 < FOM-131, and FOM-131 < FOM-132. Then, the penalty  $C'_{p_i}$  on  $W'_p$  could be added to the objective function on the second formation item. This will reduce the chance of two formation items for one pilot in a single day. (This second approach may reduce the risk of an inconsistent situation, but cannot guarantee to avoid the problem completely.)

Another modeling difficulty arises with formation items. For a pair of formation items flown together, at least one section leader must be assigned as an instructor. To simplify the model, the requirement will be modified so that all instructors who are assigned to formation items must be at least section leaders. Thus, the requirement is handled with the other instructor qualifications. This restriction in the model is not severe since most instructors are qualified as section leaders or better.

The mathematical description of the USMC model follows.

### 1. Index Sets

- $t \in T$  current date,
- $p \in P_t$  pilots (student pilots) available for training on day  $t$ ,
- $q \in Q_t$  instructors available for teaching on day  $t$ .

- $q \in Q_i$  set of instructors who are qualified to teach item  $i$ ,  
 $i \in I$  training flights (items in syllabus),  
 $i \in I_{p,t}^0$  unfinished items with no prerequisite remaining for pilot  $p$ ,  
 $i \in I_{p,t}^1$  unfinished items with exactly one prerequisite remaining for pilot  $p$ ,  
 $i \in I_{p,t} = I_{p,t}^0 \cup I_{p,t}^1$   
 set of unfinished and (potentially) allowable items,  
 $(i, i') \in II_{p,t} = \{ (i, i') \mid i \in I_{p,t}^0, i' \in I_{p,t}^1, i < i' \}$   
 set of pairs of items that are allowable and such that one is a prerequisite of the other,  
 $i \in I_F^D$  daytime formation items and  
 $i \in I_F^N$  nighttime formation items (actually only a single item).

## 2. Data

- $H_t$  flight hours goal on a day  $t$ ,  
 $h_i$  flight hours needed for syllabus item  $i$ ,  
 $\bar{I}_p$  maximum number of training items per day for pilot  $p$ ,  
 $\bar{H}_q$  maximum number of flight hours per day for instructor  $q$ ,  
 $\hat{N}_{p,t}$  current goal for items to be completed by pilot  $p$ ,  
 $N_{p,t}$  number of items completed by pilot  $p$ ,  
 $C$  objective value for penalty variable  $Z^-$  and  $Z^+$ ,  
 $C_{p,t}^1 = ( 1 + [ \max\{ 0, \hat{N}_{p,t} - N_{p,t} \} ]^2 )$ ,  
 $C_{p,t}^2 = ( 1 + [ \max\{ 0, \hat{N}_{p,t} - (N_{p,t} + 1) \} ]^2 )$  and  
 $C'_{p,t} = ( C_{p,t}^2 - C_{p,t}^1 )$ .

## 3. Decision Variables

- $X_{i,p} = \begin{cases} 1 & \text{if a student pilot } p \text{ performs item } i, \\ 0 & \text{otherwise.} \end{cases}$   
 $Y_{i,p,q} = \begin{cases} 1 & \text{if an instructor } q \text{ teaches student } p \text{ item } i, \\ 0 & \text{otherwise.} \end{cases}$   
 $W_p = \begin{cases} 1 & \text{if a student pilot } p \text{ flies two items on a given day,} \\ 0 & \text{otherwise.} \end{cases}$   
 $Z^-$  underachievement for flight hours goal,  
 $Z^+$  overachievement for flight hours goal and  
 $V, V'$  non-negative integer variables for pairing formation flights.

#### 4. Formulation

$$\text{Maximize} \quad \sum_{p \in P_t} \sum_{i \in I_{p,t}} C_{p,t}^i X_{i,p} - C'(Z^+ + Z^-) + \sum_{p \in P_t} C'_{p,t} W_p$$

$$\text{Subject to} \quad \sum_{q \in Q_t} Y_{i,p,q} - X_{i,p} = 0 \quad i \in I_{p,t}, \forall p \in P_t \quad (9)$$

$$\sum_{p \in P_t} \sum_{i \in I_{p,t}} h_i Y_{i,p,q} \leq \bar{H}_q \quad \forall q \in Q_t \quad (10)$$

$$\sum_{i \in I_{p,t}} X_{i,p} \leq \bar{I}_p \quad \forall p \in P_t \quad (11)$$

$$X_{i',p} - X_{i,p} \leq 0 \quad (i, i') \in II_{p,t}, \forall p \in P_t \quad (12)$$

$$\sum_{i \in I_{p,t}} X_{i,p} - W_p \leq 1 \quad \forall p \in P_t \quad (13)$$

$$\sum_{p \in P_t} \sum_{i \in I_F^D} X_{i,p} - 2V = 0 \quad (14)$$

$$\sum_{p \in P_t} \sum_{i \in I_F^N} X_{i,p} - 2V' = 0 \quad (15)$$

$$X_{i,p} + X_{i',p} \leq 1 \quad i, i' \in I_F^D, \forall p \in P_t \quad (16)$$

$$\sum_{p \in P_t} \sum_{i \in I_F^D} Y_{i,p,q} \leq 1 \quad \forall q \in Q_t \quad (17)$$

$$\sum_{p \in P_t} \sum_{i \in I_{p,t}} h_i X_{i,p} + Z^- - Z^+ = H_t \quad (18)$$

$$Z^+, Z^- \geq 0$$

$$V, V' \in \{0, 1, 2, \dots\}$$

$$X_{i,p} \in \{0, 1\} \quad \forall i, p$$

$$Y_{i,p,q} \in \{0, 1\} \quad \forall i, p, q$$

Constraints (9) assign exactly one instructor to each item flown. Constraints (10) limit the number of flight hours for each instructor pilot during the day. Constraints (11) limit the maximum number of training flights for each pilot during the day. Constraints (12) ensure that prerequisite items are completed before items requiring prerequisites. Constraint (13) is used to modify the objective function value if two items are performed by a pilot instead of just one. Constraint (14) limits formation flights during the daytime to an even number. Constraint (15) is analogous to constraint (14) but for nighttime formation flights. Constraints (16) ensure that a student is not paired with himself in formation flights. Constraints (17) ensure that an instructor is not paired with himself in formation flights. Constraint (18) limits the number of flight hours of the squadron to the "goal" hours of the day.

## IV. COMPUTATIONAL EXPERIENCE

All three of the models were implemented in the GAMS language. (See Appendices A, B and C.) This chapter presents the description of the data used in the GAMS program, the test runs, the computational results, and some comments for possible improvements of the models.

### A. DATA

#### 1. The JMSDF models

For the JMSDF models, with data extracted from a JMSDF document [Ref. 5], artificial data were created using the following assumptions:

1. Each pilot has an allowable set of items that is derived from a column (corresponding to a certain month) of the corresponding syllabus matrix. The current column for each pilot is chosen randomly (See Figure 3.).

Aircraft Commanders					
name	month	name	month	name	month
* Capt-Nakag	2	* Lt-Wood	2	Ltjg-Jacob	3
* Cdr-Purdue	5	* Lt-Rosentl	11	Ltjg-Wash	6
* Cdr-Larson	4	* Lt-Eagle	3	Ltjg-Lind	8
* Lcdr-Sovrn	7	Lt-Read	6	Ens-Sterling	9
* Lcdr-Walsh	8	Lt-Kang	12	Ens-Reece	10
Lcdr-Brown	1	* Lt-Armsted	5		
* Lcdr-Milch	10	Lt-Kimber	7		
Second Pilots					
name	month	name	month	name	month
Ltjg-Toi	16	Ens-Haws	12	Cdt-Novak	7
Ltjg-Johnson	15	Cdt-Powell	12	Cdt-Mcgon	2
Ltjg-Rock	3	Cdt-Snyder	12	Cdt-Sim	2
Ens-Smith	4	Cdt-Korcal	7		

\* instructors

Figure 3. Pilots and Training Period

2. Senior officers like CO or XO do not have as many flight hours available which limits  $H_{p,t}$  to a smaller value than for other pilots; for the daytime schedule,  $H_{p,t}$  for senior pilots is set to three, while for other pilots it is set to six,
3. The maximum number of items per pilot  $\bar{I}_p$  is set to five for all the aircraft commanders and four for all second pilots,
4. The scheduled day  $t$  is set to the first day of a month for the test run. Thus, the allowable items are the same items that are specified in the column of the syllabus matrix,
5. The elapsed days since last performing each item  $D_{i,t}$  were created not to violate the maximum training intervals  $\bar{D}_i$  very much, but to have some range of variability resulting from the imaginary past schedules for each pilot,

6. The number of days since the last training flight  $T_{p,t}$  is created in a similar way to  $D_{i,p,t}$ .
7. The balancing factor  $F_p$  in the objective function is set to one.
8. The weight of items  $W_i$  is fixed to 2.0 for the very critical items; 1.0 for the critical items; and 0.5 for others.
9. The number of hops available is set to 10 for each model; a total of 20 hops may be flown on day  $t$ .
10. The delay of a second pilot's progress  $DL_p$  is set to one for three out of 11 second pilots, and is zero for the rest of second pilots.
11. The number of instructors available for second pilots training may vary depending on how the scheduler allocates aircraft commanders as instructors. There exist various approaches to specify the number of available instructors. Here a simple way is taken. The asterisk in Figure 3 indicates that the pilot is qualified as an instructor; there are ten such pilots. Results from the test run of the aircraft commander model for the daytime, which is shown in Figure 4, indicate that five instructors are to fly for their own training. Among them, three pilots will use under 1.5 hours for their training, and will have time to instruct his co-pilot during the flight. Thus, the remaining five plus these three make eight, which is the number of available instructors for daytime second pilot training.

The maximum number of days for training interval  $\bar{D}_i$ , the number of training requirements for second pilots  $M_{i,p,t}$ , and the training time that is needed for each item  $h_i$  are copied from the corresponding syllabus matrix.

## 2. The USMC model

For the USMC model, data were collected from the T&R manual, vol.3 [Ref. 8], from HMT 303 and some data were created by the author. The sources for the data are detailed below:

1. The progress of the RACs in the course and the qualifications of instructors were the actual situation at HMT 303 on the third week of January, 1990. Most of the trainees were performing well over the current goals for the number of items completed, which is calculated from the 20 week training term. Consequently, the author reduced the nominal training term  $D_p$  to 14.8 weeks.
2. Prerequisite requirements were constructed as per a discussion with a scheduler at HMT 303.
3. The flight hours for each item is based on T&R manual, vol.3.
4. The goal of the total daily flight hours of the squadron was set to 24 for the day  $t$ , from the information provided by the maintenance officer.
5. The author added four imaginary RACs (who were actually expected to arrive at the squadron in February) having completed only one or two items, in order to make the situation somewhat more complicated.
6. The maximum number of flight hours available for each instructor was not collected, and was simply estimated by the author.

--- 400 PARAMETER TRAINING		SCHEDULED PILOTS AND ITEMS FOR DAYTIME									
	CAPT-NAKAG	CDR-PURDUE	LCDR-BROWN	LCDR-MILCH	LT-WOOD	LT-ROSENTL	LT-KANG	LT-KIMBER	LTJG-JACOB	LTJG-LIND	
B2221D			1.000				1.000		1.000		
B2222D	1.000	1.000			1.000	1.000				1.000	
B2225D						1.000					
B2224D	1.000				1.000						
B2225D	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
B2226D	1.000		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
B2522D		1.000									
B2525D			1.000					1.000	1.000		
B5120D			1.000	1.000				1.000			
B5150D				1.000				1.000			
B-121D										1.000	
B-122D		1.000		1.000							
B7160D	1.000	1.000			1.000	1.000				1.000	
--- 401 PARAMETER TIME		EXPECTED DAYTIME TRAINING TIME									
CAPT-NAKAG	1.500,	CDR-PURDUE	1.800,	LCDR-BROWN	2.100,	LCDR-MILCH	2.600,	LT-WOOD	1.500,	LT-ROSENTL	1.500
LT-KANG	0.800,	LT-KIMBER	2.400,	LTJG-JACOB	1.100,	LTJG-LIND	1.600				
--- 402 PARAMETER HAPPYGVN		SCHEDULED PILOTS FOR DAYTIME									
CAPT-NAKAG	1.000,	CDR-PURDUE	1.000,	LCDR-BROWN	1.000,	LCDR-MILCH	1.000,	LT-WOOD	1.000,	LT-ROSENTL	1.000
LT-KANG	1.000,	LT-KIMBER	1.000,	LTJG-JACOB	1.000,	LTJG-LIND	1.000				
--- 403 PARAMETER INSTR		SCHEDULED INSTRUCTORS									
CAPT-NAKAG	1.000,	CDR-PURDUE	1.000,	LCDR-MILCH	1.000,	LT-WOOD	1.000,	LT-ROSENTL	1.000		

Figure 4. Results of JMSDF Aircraft Commander Model (HSS-2B)

7. The weight for the penalty variables  $Z^+$  and  $Z^-$  is set to one tentatively.

## B. PROGRAM TEST RUNS

The coded GAMS programs were run on an IBM3033(AP) under VM/CMS at the Naval Postgraduate School. The JMSDF models run with a virtual storage of 2 megabytes. For the JMSDF aircraft commander model, in which 19 pilots are to be scheduled, a program with 129 variables and 477 constraints is solved in 2.3 seconds. Both

aircraft commander and second pilot model give integer solutions and the optimality gaps are fairly small.

The USMC model also needs 2 megabyte storage to generate. (If the number of students increases or the model is expanded in some way, 3 megabytes of storage might become necessary.) In attempting to solve the basic problem, the ZOOM solver is interrupted and does not iterate to the best integer solution. Taking the weaker approach to ensure the feasible pairing of formation flights, i.e., deleting constraints (16), and (17), and with a modified objective function, a normal completion with an integer solution is reached. Instead of using  $+\sum_p C'_{p,t}W_p$  in the objective function, the items that have one prerequisite remaining at the beginning of day  $t$  are summed with smaller coefficient  $C^2_{p,t}$ . i.e., the objective function is:

$$\text{Maximize } \sum_p \sum_{i \in I_{p,t}^0} C_{p,t}^1 X_{ip} + \sum_p \sum_{i \in I_{p,t}^1} C_{p,t}^2 X_{ip} - C'(Z^+ + Z^-).$$

The items which have no prerequisites remaining are multiplied by the possibly larger coefficient  $C_{p,t}^1$ . Then, the USMC model, involving 11 RACs and 15 instructors, results in a program with 984 variables and 146 constraints which is solved in 23.5 seconds.

## C. RESULTS

### 1. The JMSDF Models

Sample results for the JMSDF aircraft commander model (daytime part) are shown in Figure 4. The first part of this figure, the table labeled "400 PARAMETER TRAINING," tells who is going to fly on a day  $t$  and which items are to be performed. "1.000" in the table indicates the scheduled combinations of items and pilots; blanks in the table and all other allowable combinations which are not shown in the table imply zero which means not to schedule the remaining combinations. Ten out of 19 pilots are scheduled to fly. The next table labeled "401 PARAMETER TIME" indicates how long it takes to complete each pilot's flight. The third table labeled "402 PARAMETER HAPPYGUY" simply lists the names of scheduled pilots. The fourth table labeled "403 PARAMETER INSTR" indicates which scheduled pilot has an instructor qualification so that the schedulers would know which instructors would be available for second pilot training.

### 2. The USMC Model

The results of the USMC model are also shown in Figure 5. This time the first table labeled "574 PARAMETER TRAINING" tells which student pilot is going to do

574 PARAMETER TRAINING ITEMS AND STUDENTS										
	DARLING	SHEERIN	STEININGER	MENSEL	MILNE	ADAMS	ROSENTL	EAGLE	READ	KANG
FAM100									1.000	
FAM101							1.000		1.000	1.000
FAM102							1.000	1.000		1.000
FAM109		1.000								
INS121	1.000									
FOM150	1.000	1.000	1.000	1.000	1.000	1.000				
NAV151				1.000		1.000				
NAV152					1.000					

575 PARAMETER SECOND EXCLUSIVE SECOND ITEM			
	ROSENTL	READ	KANG
FAM101		1.000	
FAM102	1.000		1.000

576 PARAMETER TEACHER ITEMS - STUDENTS AND INSTRUCTORS										
	GULMAN	CASTEEL	HALL	WEST	SCALESINGR	FORD	JONES	HENDRICK	OHENS	
FAM100.READ				1.000						
FAM101.ROSENTL						1.000				
FAM101.READ			1.000							
FAM101.KANG			1.000							
FAM102.ROSENTL			1.000							
FAM102.EAGLE		1.000								
FAM102.KANG		1.000								
FAM109.SHEERIN						1.000				
INS121.DARLING										1.000
FOM150.DARLING										1.000
FOM150.SHEERIN					1.000					
FOM150.STEININGER						1.000				
FOM150.MENSEL					1.000					
FOM150.MILNE			1.000							
FOM150.ADAMS					1.000					
NAV151.MENSEL									1.000	
NAV151.ADAMS							1.000			
NAV152.MILNE							1.000			

578 VARIABLE ZP.L	=	0.000 OVERACHIEVEMENT FOR FLIGHT HOURS GOAL
579 VARIABLE ZM.L	=	0.000 UNDERACHIEVEMENT FOR FLIGHT HOURS GOAL
580 VARIABLE V.L	=	3.000 DAYTIME FORMATION ORGANIZER
581 VARIABLE W.L	=	0.000 NIGHTTIME FORMATION ORGANIZER

Figure 5. Results of USMC Model (AH-1J)

which items. Ten out of eleven student pilots are scheduled for one or two items. The solution shows that many formation flights are listed because those items take only one hour, while other items take more than one and a half hours. Therefore the solver pushes shorter items in the 24 hour time frame. In practice, formation flights may not be appropriate choice to conduct on day  $t$ , because many FAM or INST categories, which are more basic categories than FORM, are still unfinished and allowable for most of the students. Further discussion on this topic will be presented in the next section. The second table labeled "575 PARAMETER SECOND" lists the scheduled items that have one prerequisite remaining. Thus, these items are exclusively the second item of a day. The third table labeled "576 PARAMETER TEACHER" shows which instructor is assigned to which item and student combination. The total flight hours on day  $t$  equals the goal of 24 since the values of  $Z^-$  and  $Z^+$  are both zero as shown in the lines labeled "578 VARIABLE ZP.L" and "579 VARIABLE ZM.L." The last two lines labeled "580 VARIABLE V.L" and "581 VARIABLE VV.L" show the number of pairs of formation flights during the day is three, and during the night is zero.

#### D. PRACTICAL ASPECTS AND EXTENSIONS

Since the models do not directly schedule everything, further effort by a human scheduler is necessary. For the JMSDF model, the combination of an aircraft commander and a second pilot must be dealt with manually. Take-off time or duration of flights have not been modeled. A scheduled aircraft commander (or an instructor) and a second pilot (or a student pilot) may not be compatible for the same flight with a particular take-off time and duration because of the schedule of administrative work on the ground. Thus, it may be necessary to further modify the pilot's combinations. To refine the models the data or formulations can be modified as discussed below.

##### 1. The JMSDF Models

1. The maximum number of items in a day  $\bar{I}_p$  could be specified depending on a pilot's strengths or weaknesses or, if he is a second pilot, where in the syllabus his training is currently taking place.
2. The balancing factor in the objective function coefficient  $C'_{p,t}$  could be modified in consecutive experiments with the models.
3. There could exist disallowed combinations of items for training purposes. So far only nighttime and daytime items have been split, but other disallowed items, say  $i$  and  $i'$  could be excluded by adding the constraint  $X_{i,p} + X_{i',p} \leq 1$ .

## 2. The USMC Model

1. A weight associated with selecting an instructor has not yet been modeled. A criterion could be introduced for maintaining the currency of instructors; i.e., schedule instructors who have relatively less currency for each syllabus category. As a data, the number of days since last performing an item  $i$  in category  $c(i)$  is denoted  $R_{c(i)qt}$ . This can be used directly as a weight on  $Y_{ipq}$  since as  $R_{c(i)qt}$  becomes larger item  $i$  for instructor  $q$  should become more likely to be chosen. For simplicity, only three categories of currency  $c$  are considered, namely "night" items, "terrain flight" items and "other" items.
2. It may be the policy for a student pilot to be exposed to as many instructors as possible. This could be handled by modifying the weight on  $Y_{ipq}$  to be larger for student instructor pairs which have not occurred or have not occurred as often as other pairings. The number of flights in which student  $p$  flew with instructor  $q$  is denoted  $E_{pqt}$ , and a weight on  $Y_{ipq}$  could be defined as

$$F_{pqt} = \frac{1}{a + E_{pqt}}, \quad \text{where } a \text{ is a positive constant.}$$

3. The weight defined thus far for  $X_{ip}$  does not depend on which item is selected. It only changes between student pilots, and if student flies one item or two. This may not be appropriate. The solution may push as many items as possible into a 24 hour time frame resulting in many short formation flights being scheduled. In order to avoid this tendency, an exogenous factor, say,  $W_i$ , could multiplicatively modify the original weight  $C_{pt}^1$  or  $C_{pt}^2$ . Thus,

$$C_{ipt}^1 = W_i C_{pt}^1, \quad C_{ipt}^2 = W_i C_{pt}^2.$$

The above weight factors were tested in a modified model. In the objective function, the term  $C_p W_p$  is again deleted, and the modified MOE is used as in the first successful test run. Then the objective function is:

$$\begin{aligned} \text{Maximize} \quad & \sum_{p \in P_t} \sum_{i \in I_{pt}^0} C_{ipt}^1 X_{ip} + \sum_{p \in P_t} \sum_{i \in I_{pt}^1} C_{ipt}^2 X_{ip} - C'(Z^+ + Z^-) \\ & + \sum_{i \in I_{pt}} \sum_{p \in P_t} \sum_{q \in Q_t^i} (R_{c(i)qt} + F_{pqt}) Y_{ipq}. \end{aligned}$$

Though the basic model for HMT 303 does not run properly in GAMS, the model modifications above were tested with additional artificially created data. For formation flights, constraints (16) and (17) which are deleted in the test of the basic USMC model were added too. The additional parameters and equations are listed in Appendix D. The GAMS program runs and reaches an optimal integer solution (See Figure 6).

The ZOOM solver selects a different set of items and different combination of students and instructors, according to the modified criteria. The selected items are affected by the

706 PARAMETER TRAINING		ITEMS AND STUDENTS								
	DARLING	SHEERIN	STEINDYGER	PANTEN	MENSEL	MILNE	ADAMS	ROSENTL	EAGLE	READ
FAM100										1.000
FAM101								1.000		1.000
FAM102									1.000	
FAM106					1.000		1.000			
FAM107	1.000						1.000			
FAM109		1.000								
FAM110			1.000							
MVG181						1.000				
MVG182				1.000		1.000				
* KANG										
FAM101	1.000									
708 PARAMETER TEACHER		ITEMS - STUDENTS AND INSTRUCTORS								
		GULMAN	CASTEEL	HALL	SCHLESINGR	FORD	JONES	HENDRICK	OMENS	GRACE
FAM100.PEAO						1.000				
FAM101.ROSENTL									1.000	
FAM101.READ						1.000				
FAM101.KANG										1.000
FAM102.EAGLE									1.000	
FAM106.MENSEL					1.000					
FAM106.ADAMS				1.000						
FAM107.DARLING			1.000							
FAM107.ADAMS										1.000
FAM109.SHEERIN								1.000		
FAM110.STEINDYGER							1.000			
MVG181.MILNE		1.000								
MVG182.MILNE		1.000								
* ORNER										
MVG182.PANTEN		1.000								
---	710 VARIABLE ZP.L									= 0.000 OVERACHIEVEMENT FOR FLIGHT HOURS GOAL
---	711 VARIABLE ZM.L									= 1.000 UNDERACHIEVEMENT FOR FLIGHT HOURS GOAL
---	712 VARIABLE V.L									= 0.000 DAYTIME FORMATION ORGANIZER
---	715 VARIABLE VV.L									= 0.000 NIGHTTIME FORMATION ORGANIZER

Figure 6. Results of a modified USMC Model (AH-1J)

exogenous weight  $W_i$  significantly, and five out of 14 items are night items to update "night" currency of instructors. Total flight hours is 23 hours this time, which is one hour under the goal.

## E. CONCLUSIONS

These prototypic models demonstrate the feasibility of semi-automated training flight scheduling in military flight squadrons. Although the models are not the final product for the use of flight squadron schedulers, the listing of the daily flight items and associated pilots could save a lot of time for these schedulers. Additional work with actual squadrons could result in modified model parameters or even in the addition or deletion of constraints. Some possible examples of this have been shown. Also, it would probably be necessary to implement an efficient database management system to maintain flight records and the like for these models to be utilized in practice.

## APPENDIX A.

*GAMS program listing of the Aircraft Commander Model for the JMSDF*

\$TITLE Model 1 (Aircraft Commanders) - Day - Night - JMSDF

\$OFFUPPER OFFSYMXREF OFFSYMLIST

OPTIONS SOLPRINT = Off , SYSOUT = ON

OPTIONS LIMCOL = 0 , LIMROW = 0

\* This is a integer programming type event scheduling problem.

\* This is aircraft commander model.

\* Daily schedule computed will be the most urgent set of syllabus items,  
\* subject to aircraft and pilot availability.

\* Daytime and nighttime schedule for tomorrow will be solved separately.

SETS

i items of syllabus (23)

/ B2221D,	B2221N,	B2222D,	B2222N,	B2223D,	B2224D,	B2224N,	B2225D	
B2226D,	B2321D,	B2322D,	B2322N,	B2323D,	B2323N,	B3120D,	B3120N	
B3130D,	B3130N,	B5421D,	B6121D,	B6122D,	B6122N,	B7160D		/

DY(I) daytime items (15)

/ B2221D,	B2222D,	B2223D,	B2224D,	B2225D,	B2226D,	B2321D,	B2322D	
B2323D,	B3120D,	B3130D,	B5421D,	B6121D,	B6122D,	B7160D		/

NITE(I) nighttime items (8)

/ B2221N,	B2222N,	B2224N,	B2322N,	B2323N,	B3120N,	B3130N,	B6122N	/
-----------	---------	---------	---------	---------	---------	---------	--------	---

P pilots (19)

/ CAPT-NAKAG,	CDR-PURDUE,	CDR-LARSON,	LCDR-SOVRN,	LCDR-WALSH	
LCDR-BROWN,	LCDR-MILCH,	LT-WOOD,	LT-ROSENTL,	LT-EAGLE	
LT-READ,	LT-KANG,	LT-ARMSTED,	LT-KIMBER,	LTJG-JACOB	
LTJG-WASH,	LTJG-LIND,	ENS-STERLG,	ENS-REECE		/ ;

PARAMETERS

HBARD(P) maximum flight hours per day for a pilot

/ CAPT-NAKAG	3,	CDR-PURDUE	3,	CDR-LARSON	6
LCDR-SOVRN	6,	LCDR-WALSH	6,	LCDR-BROWN	6
LCDR-MILCH	6,	LT-WOOD	6,	LT-ROSENTL	6
LT-EAGLE	6,	LT-READ	6,	LT-KANG	6
LT-ARMSTED	6,	LT-KIMBER	6,	LTJG-JACOB	6
LTJG-WASH	6,	LTJG-LIND	6,	ENS-STERLG	6
ENS-REECE	6				/

HBARN(P) maximum flight hours per night for a pilot

/ CAPT-NAKAG	2.5,	CDR-PURDUE	2.5,	CDR-LARSON	2.5
LCDR-SOVRN	2.5,	LCDR-WALSH	2.5,	LCDR-BROWN	2.5
LCDR-MILCH	2.5,	LT-WOOD	2.5,	LT-ROSENTL	2.5
LT-EAGLE	2.5,	LT-READ	2.5,	LT-KANG	2.5
LT-ARMSTED	2.5,	LT-KIMBER	2.5,	LTJG-JACOB	2.5
LTJG-WASH	2.5,	LTJG-LIND	2.5,	ENS-STERLG	2.5
ENS-REECE	2.5				/

H(I) training time that is needed for item I

/	B2221D 0.2,	B2221N 0.2,	B2222D 0.2,	B2222N 0.2
	B2223D 0.2,	B2224D 0.2,	B2224N 0.2,	B2225D 0.3
	B2226D 0.3,	B2321D 1.5,	B2322D 0.5,	B2322N 0.5
	B2323D 0.3,	B2323N 0.3,	B3120D 1.0,	B3120N 1.0
	B3130D 0.5,	B3130N 0.5,	B5421D 0.7,	B6121D 0.5
	B6122D 0.5,	B6122N 0.5,	B7160D 0.3	/

IBAR(P) maximum number of training items per day for each pilot

/	CAPT-NAKAG 5,	CDR-PURDUE 5,	CDR-LARSON 5
	LCDR-SOVRN 5,	LCDR-WALSH 5,	LCDR-BROWN 5
	LCDR-MILCH 5,	LT-WOOD 5,	LT-ROSENTL 5
	LT-EAGLE 5,	LT-READ 5,	LT-KANG 5
	LT-ARMSTED 5,	LT-KIMBER 5,	LTJG-JACOB 5
	LTJG-WASH 5,	LTJG-LIND 5,	ENS-STERLG 5
	ENS-REECE 5		/

T(P) number of days since each pilot's last flight

/	CAPT-NAKAG 5,	CDR-PURDUE 4,	CDR-LARSON 2
	LCDR-SOVRN 3,	LCDR-WALSH 1,	LCDR-BROWN 6
	LCDR-MILCH 8,	LT-WOOD 5,	LT-ROSENTL 5
	LT-EAGLE 3,	LT-READ 3,	LT-KANG 5
	LT-ARMSTED 2,	LT-KIMBER 4,	LTJG-JACOB 7
	LTJG-WASH 2,	LTJG-LIND 4,	ENS-STERLG 3
	ENS-REECE 2		/

W(I) criticality of item I

/	B2221D 0.5,	B2221N 2.0,	B2222D 1.0,	B2222N 1.0
	B2223D 0.5,	B2224D 0.5,	B2224N 2.0,	B2225D 3.0
	B2226D 1.0,	B2321D 0.5,	B2322D 0.5,	B2322N 0.5
	B2323D 0.5,	B2323N 0.5,	B3120D 1.0,	B3120N 2.0
	B3130D 0.5,	B3130N 0.5,	B5421D 0.5,	B6121D 0.5
	B6122D 0.7,	B6122N 0.7,	B7160D 1.0	/

DBAR(I) maximum training interval for item I (days)

/	B2221D 90,	B2221N 45,	B2222D 90,	B2222N 90
	B2223D 210,	B2224D 120,	B2224N 90,	B2225D 30
	B2226D 45,	B2321D 365,	B2322D 120,	B2322N 120
	B2323D 60,	B2323N 60,	B3120D 90,	B3120N 90
	B3130D 90,	B3130N 90,	B5421D 365,	B6121D 180
	B6122D 180,	B6122N 180,	B7160D 180	/ ;

TABLE

M(I,P) allowable items based on monthly set of items for pilot P

	CAPT-NAKAG	CDR-PURDUE	CDR-LARSON	LCDR-SOVRN	LCDR-WALSH
B2221D	0	0	1	1	0
B2221N	1	1	1	1	1
B2222D	1	1	0	0	1
B2222N	0	0	0	0	0
B2223D	0	0	1	0	0
B2224D	1	0	0	0	0
B2224N	0	0	1	1	0
B2225D	1	1	1	1	1
B2226D	1	1	1	1	1
B2321D	0	0	0	0	0

B2322D	0	1	0	0	0
B2322N	0	0	0	1	0
B2323D	0	1	0	1	0
B2323N	1	0	1	0	1
B3120D	0	0	1	1	0
B3120N	1	1	0	0	1
B3130D	0	0	1	1	0
B3130N	1	1	0	0	1
B5421D	0	0	0	0	0
B6121D	1	0	0	0	1
B6122D	0	1	0	0	0
B6122N	0	0	1	0	0
B7160D	1	1	0	0	1

+	LCDR-BROWN	LCDR-MILCH	LT-WOOD	LT-ROSENTL	LT-EAGLE
B2221D	1	1	0	0	1
B2221N	1	1	1	1	0
B2222D	0	0	1	1	0
B2222N	0	0	0	0	1
B2223D	0	0	0	1	0
B2224D	0	1	1	0	0
B2224N	1	1	0	0	1
B2225D	1	1	1	1	1
B2226D	1	1	1	1	1
B2321D	0	0	0	0	0
B2322D	1	0	0	0	0
B2322N	0	0	0	1	1
B2323D	1	0	0	1	1
B2323N	0	1	1	0	0
B3120D	1	1	0	0	0
B3120N	0	0	1	1	0
B3130D	1	1	0	0	0
B3130N	0	0	1	1	0
B5421D	0	0	0	0	0
B6121D	0	0	1	1	0
B6122D	0	1	0	0	0
B6122N	0	0	0	0	0
B7160D	0	0	1	1	0

+	LT-READ	LT-KANG	LT-ARMSTED	LT-KIMBER	LTJG-JACOB
B2221D	1	1	0	1	1
B2221N	0	0	1	1	0
B2222D	0	0	1	0	0
B2222N	1	1	0	0	1
B2223D	0	0	0	0	0
B2224D	1	0	0	0	0
B2224N	0	0	0	1	1
B2225D	1	1	1	1	1
B2226D	1	1	1	1	1
B2321D	1	0	0	0	0
B2322D	0	0	1	0	0
B2322N	0	0	0	1	1
B2323D	0	0	1	1	1
B2323N	1	1	0	0	0
B3120D	0	0	0	1	0
B3120N	0	0	1	0	0

B3130D	0	0	0	1	0
B3130N	0	0	1	0	0
B5421D	1	0	0	0	0
B6121D	0	0	0	0	0
B6122D	0	0	1	0	0
B6122N	0	0	0	0	0
B7160D	0	0	1	0	0

+	LTJG-WASH	LTJG-LIND	ENS-STERLG	ENS-REECE	
B2221D	1	0	1	1	
B2221N	0	1	0	1	
B2222D	0	1	0	0	
B2222N	1	0	1	0	
B2223D	0	0	0	0	
B2224D	1	0	0	1	
B2224N	0	0	1	1	
B2225D	1	1	1	1	
B2226D	1	1	1	1	
B2321D	1	0	0	0	
B2322D	0	0	1	0	
B2322N	0	0	0	0	
B2323D	0	0	1	0	
B2323N	1	1	0	1	
B3120D	0	0	0	1	
B3120N	0	1	0	0	
B3130D	0	0	0	1	
B3130N	0	1	0	0	
B5421D	0	0	0	0	
B6121D	0	1	0	0	
B6122D	0	0	0	1	
B6122N	0	0	1	0	
B7160D	0	1	0	0	;

TABLE  
DAY(I,P) number of days since the last training of item I

	CAPT-NAKAG	CDR-PURDUE	CDR-LARSON	LCDR-SOVRN	LCDR-WALSH
B2221D	13	11	25	20	9
B2221N	22	23	36	39	15
B2222D	30	63	48	46	85
B2222N	30	45	6	7	56
B2223D	30	25	90	80	99
B2224D	30	97	48	11	34
B2224N	22	51	6	70	15
B2225D	5	11	23	11	9
B2226D	13	11	23	20	9
B2321D	30	150	90	5	74
B2322D	13	100	69	46	85
B2322N	30	75	6	105	15
B2323D	5	35	23	46	22
B2323N	30	23	77	7	56
B3120D	14	15	69	80	22
B3120N	30	75	35	39	65
B3130D	5	15	80	65	22
B3130N	30	75	35	39	65
B5421D	30	150	90	11	34

B6121D	30	63	69	132	165
B6122D	30	150	90	35	85
B6122N	30	23	90	70	105
B7160D	30	63	77	46	85

+	LCDR-BROWN	LCDR-MILCH	LT-WOOD	LT-ROENTL	LT-EAGLE
B2221D	10	25	12	21	57
B2221N	10	43	9	4	21
B2222D	10	60	36	64	11
B2222N	10	35	36	42	66
B2223D	10	160	36	187	66
B2224D	10	88	36	21	11
B2224N	10	22	9	4	57
B2225D	10	25	12	10	11
B2226D	10	22	12	25	28
B2321D	10	110	36	125	66
B2322D	10	6	36	49	40
B2322N	10	65	36	117	66
B2323D	10	6	22	41	35
B2323N	10	43	36	4	21
B3120D	10	68	22	14	44
B3120N	10	35	36	51	18
B3130D	10	78	22	21	57
B3130N	10	43	36	51	25
B5421D	10	112	36	125	66
B6121D	10	32	36	71	9
B6122D	10	130	36	14	66
B6122N	10	12	36	32	66
B7160D	10	48	36	71	11

+	LT-READ	LT-KANG	LT-ARMSTED	LT-KIMBER	LTJG-JACOB
B2221D	42	33	21	2	42
B2221N	17	21	23	37	21
B2222D	24	13	69	32	6
B2222N	67	74	57	13	63
B2223D	33	11	54	67	63
B2224D	99	33	21	5	10
B2224N	51	21	23	65	37
B2225D	11	12	21	17	10
B2226D	24	12	8	17	10
B2321D	163	177	126	16	63
B2322D	19	62	92	34	48
B2322N	83	19	36	109	63
B2323D	28	18	37	38	48
B2323N	51	54	7	13	12
B3120D	46	56	10	86	39
B3120N	14	24	63	54	37
B3130D	37	56	10	86	48
B3130N	14	24	63	54	12
B5421D	163	175	126	16	63
B6121D	108	12	77	134	23
B6122D	17	34	126	55	63
B6122N	51	177	9	76	63
B7160D	14	21	77	45	23

+	LTJG-WASH	LTJG-LIND	ENS-STERLG	ENS-REECE
B2221D	56	23	54	4
B2221N	26	17	12	34
B2222D	14	74	7	45
B2222N	67	52	76	12
B2223D	45	110	139	166
B2224D	95	63	64	98
B2224N	38	42	54	12
B2225D	9	10	9	6
B2226D	14	10	7	4
B2321D	157	30	73	104
E2322D	24	77	104	14
B2322N	76	19	54	67
B2323D	24	10	33	23
B2323N	38	57	20	35
B3120D	39	20	41	73
B3120N	11	80	5	45
B3130D	35	19	41	74
B3130N	7	80	5	42
B5421D	157	40	73	110
B6121D	97	166	12	46
B6122D	17	76	98	132
B6122N	39	110	165	150
B7160D	11	75	15	45

SCALAR

FCTR      balancing factor for the objective functions      / 1 /  
DHELO      number of flights (hops) available for the day      / 10 /  
NHELO      number of flights (hops) available for the night      / 6 / ;

PARAMETER

COST(I,P)      criticality of training items for each pilot  
COSTA(P)      criticality to refly for each pilot ;

COST(I,P) \$ ( DAY(I,P) LT DBAR(I) )  
                 = W(I) \* M(I,P) \* DAY(I,P) / DBAR(I) ;  
COST(I,P) \$ ( DAY(I,P) GE DBAR(I) )  
                 = W(I) \* M(I,P) \* ( DAY(I,P) / DBAR(I) ) \*\* 2 ;  
COSTA(P) = FCTR \* T(P) ;

DISPLAY COST;

SETS

IPD(I,P)      allowable items for daytime schedule  
IPN(I,P)      allowable items for night schedule ;

IPD(I,P) = YES \$ ( M(I,P) \$ DY(I) EQ 1 ) ;  
IPN(I,P) = YES \$ ( M(I,P) \$ NITE(I) EQ 1 ) ;

BINARY VARIABLE

X(I,P)      one if pilot P performs item I otherwise zero  
Y(P)      one if pilot P flies on that day otherwise zero ;

VARIABLES

PROFT schedule MOE ;

EQUATIONS

DOBJ objective function for daytime schedule  
 DHOURL(P) maximum flight hours for each pilot  
 DITEM(P) maximum items for each flight  
 DCOMP(I,P) performing items implies to fly  
 DHOPNO aircraft availability (number of hops)

NOBJ objective function of nighttime schedule  
 NHOURL(P) maximum flight hours for each pilot (night)  
 NITEM(P) maximum items for each flight  
 NCOMP(I,P) performing items implies to fly  
 NHOPNO aircraft availability (number of hops) ;

\* daytime scheduling formulation

\* maximize

DOBJ.. PROFT =E= SUM ((I, P), COST(I,P) \* X(I,P) \$ IPD(I,P))  
 + SUM ( P, COSTA(P) \* Y(P) ) ;

\* subject to

DHOURL(P).. SUM( I, H(I) \* X(I,P) \$ IPD(I,P)) =L= HBARD(P) ;  
 DITEM(P).. SUM( I, X(I,P) \$ IPD(I,P)) =L= IBAR(P) ;  
 DHOPNO.. SUM( P, Y(P) ) =L= DHELO ;  
 DCOMP(I,P).. X(I,P) \$ IPD(I,P) - Y(P) =L= 0 ;

\* nighttime scheduling model

\* maximize

NOBJ.. PROFT =E= SUM ((I, P), COST(I,P) \* X(I,P) \$ IPN(I,P))  
 + SUM ( P, COSTA(P) \* Y(P) ) ;

\* subject to

NHOURL(P).. SUM( I, H(I) \* X(I,P) \$ IPN(I,P)) =L= HBARN(P) ;  
 NITEM(P).. SUM( I, X(I,P) \$ IPN(I,P)) =L= IBAR(P) ;  
 NHOPNO.. SUM( P, Y(P) ) =L= NHELO ;  
 NCOMP(I,P).. X(I,P) \$ IPN(I,P) - Y(P) =L= 0 ;

MODEL ACDAY aircraft commander daytime model  
 / DHOURL, DITEM, DHOPNO, DCOMP, DOBJ /

ACNGT aircraft commander nighttime model  
 / NHOURL, NITEM, NHOPNO, NCOMP, NOBJ / ;

SOLVE ACDAY USING MIP MAXIMIZING PROFT;

\* report in tabular format

PARAMETER

TRAINING(I,P) scheduled pilots and items for daytime  
 TIME(P) expected daytime training time  
 HAPPYGUY(P) scheduled pilots for daytime  
 INSTR(P) scheduled instructors ;

```

PARAMETER
  INSTRUCT(P)      qualified instructor
  / CAPT-NAKAG     1,      CDR-PURDUE      1,      CDR-LARSON      1
  LCDR-SOVRN       1,      LCDR-WALSH    1,      LCDR-BROWN      0
  LCDR-MILCH       1,      LT-WOOD      1,      LT-ROSENTL     1
  LT-EAGLE         1,      LT-READ     0,      LT-KANG         0
  LT-ARMSTED       1,      LT-KIMBER   0,      LTJG-JACOB     0
  LTJG-WASH        0,      LTJG-LIND   0,      ENS-STERLG     0
  ENS-REECE        0 / ;

```

```

  TRAINING(I,P) = X.L(I,P) ;
  TIME(P)       = SUM ( I, H(I) * X.L(I,P)) ;
  HAPPYGUY(P)   = Y.L(P) ;
  INSTR(P)      = INSTRUCT(P) $ Y.L(P) ;

```

```

DISPLAY TRAINING ;
DISPLAY TIME     ;
DISPLAY HAPPYGUY ;
DISPLAY INSTR    ;

```

SOLVE ACNGT USING MIP MAXIMIZING PROFIT;

\* report in tabular format

```

PARAMETER
  DOIT(I,P)      scheduled pilots and items for nighttime
  NTIME(P)       expected night training time
  OWLS(P)        scheduled pilots for nighttime ;

  DOIT(I,P)      = X.L(I,P) $ IPN(I,P) ;
  NTIME(P)       = SUM ( I, H(I) * X.L(I,P) $ IPN(I,P)) ;
  OWLS(P)        = Y.L(P) $ ( SUM ( I, X.L(I,P) $ IPN(I,P))) ;
  INSTR(P)       = INSTRUCT(P) $ OWLS(P) ;

```

```

DISPLAY DOIT    ;
DISPLAY NTIME   ;
DISPLAY OWLS    ;
DISPLAY INSTR   ;

```

## APPENDIX B.

*GAMS program listing of the Second Pilot Model for the JMSDF*

\$TITLE Model 2 (Second Pilots) - Day - Night - JMSDF

\$OFFUPPER OFFSYMXREF OFFSYMLIST

OPTIONS SOLPRINT = Off

OPTIONS LIMCOL = 0 , LIMROW = 0

\* This is an integer programming type event scheduling problem.

\* This is a second pilot model.

\* Daily schedule computed will be the most urgent set of syllabus items,  
\* subject to aircraft, instructor and trainee availability.

\* Daytime and nighttime schedule for tomorrow are to be solved separately.

SETS

I items of syllabus (39)

/ B2210D, B2221D, B2221N, B2222D, B2222N, B2223D, B2224D  
B2224N, B2225D, B2225H, B2226D, B2231D, B2321D, B2322D  
B2322N, B2323D, B2323N, B2400D, B3220D, B3220N, B3111D  
B3112D, B3113D, B3114D, B3120D, B3120N, B3130D, B3130N  
B3140D, B3150D, B3150N, B5421D, B6121D, B6122D, B6122N  
B7160D, B7160N, B0021D, B0022D /

DY(I) daytime items (28)

/ B2210D, B2221D, B2222D, B2223D, B2224D, B2225D  
B2225H, B2226D, B2231D, B2321D, B2322D, B2323D  
B2400D, B3220D, B3111D, B3112D, B3113D, B3114D  
B3120D, B3130D, B3140D, B3150D, B5421D, B6121D  
B6122D, B7160D, B0021D, B0022D /

NITE(I) nighttime items (11)

/ B2221N, B2222N, B2224N, B2322N, B2323N, B3220N  
B3120N, B3130N, B3150N, B6122N, B7160N /

P second pilots (11)

/ LTJG-TOI, LTJG-JOHN, LTJG-ROCK  
ENS-SMITH, ENS-HAWS, CDT-POWELL  
CDT-SNYDER, CDT-KORCAL, CDT-NOVAK  
CDT-MCGON, CDT-SIM / ;

PARAMETERS

HBARD(P) maximum flight hours on a day for a second pilot

/ LTJG-TOI 6 , LTJG-JOHN 6 , LTJG-ROCK 6 , ENS-SMITH 6  
ENS-HAWS 6 , CDT-POWELL 6 , CDT-SNYDER 6 , CDT-KORCAL 6  
CDT-NOVAK 6 , CDT-MCGON 6 , CDT-SIM 6 /

HBARN(P) maximum flight hours at night for a second pilot

/ LTJG-TOI 2.5, LTJG-JOHN 2.5, LTJG-ROCK 2.5, ENS-SMITH 2.5  
ENS-HAWS 2.5, CDT-POWELL 2.5, CDT-SNYDER 2.5, CDT-KORCAL 2.5  
CDT-NOVAK 2.5, CDT-MCGON 2.5, CDT-SIM 2.5 /

H(I) training time that is needed for item I

/	B2210D	1.5,	B2221D	0.2,	B2221N	0.5,	B2222D	0.4
	B2222N	0.6,	B2223D	0.3,	B2224D	0.2,	B2224N	0.5
	B2225D	0.3,	B2225H	0.5,	B2226D	0.3,	B2231D	1.0
	B2321D	1.5,	B2322D	0.5,	B2322N	0.5,	B2323D	0.3
	B2323N	0.3,	B2400D	0.5,	B3220D	2.0,	B3220N	2.0
	B3111D	1.0,	B3112D	0.5,	B3113D	1.0,	B3114D	0.5
	B3120D	1.0,	B3120N	1.0,	B3130D	0.5,	B3130N	0.5
	B3140D	1.0,	B3150D	0.5,	B3150N	0.5,	B5421D	0.7
	B6121D	0.5,	B6122D	0.5,	B6122N	0.5,	B7160D	0.3
	B7160N	0.3,	B0021D	0.7,	B0022D	1.0		/

IBAR(P) maximum number of training items per flight for a second pilot

/	LTJG-TOI	4,	LTJG-JOHN	4,	LTJG-ROCK	4,	ENS-SMITH	4
	ENS-HAWS	4,	CDT-POWELL	4,	CDT-SNYDER	4,	CDT-KORCAL	4
	CDT-NOVAK	4,	CDT-MCGON	4,	CDT-SIM	4		/

T(P) number of days since each second pilot's last flight

/	LTJG-TOI	3,	LTJG-JOHN	3,	LTJG-ROCK	4,	ENS-SMITH	3
	ENS-HAWS	1,	CDT-POWELL	5,	CDT-SNYDER	5,	CDT-KORCAL	4
	CDT-NOVAK	6,	CDT-MCGON	2,	CDT-SIM	3		/

DBAR(I) maximum training interval for item I (days)

/	B2210D	365,	B2221D	30,	B2221N	30,	B2222D	30
	B2222N	60,	B2223D	270,	B2224D	30,	B2224N	60
	B2225D	270,	B2225H	365,	B2226D	60,	B2231D	365
	B2321D	180,	B2322D	90,	B2322N	150,	B2323D	90
	B2323N	120,	B2400D	420,	B3220D	90,	B3220N	120
	B3111D	120,	B3112D	120,	B3113D	120,	B3114D	120
	B3120D	500,	B3120N	500,	B3130D	500,	B3130N	500
	B3140D	500,	B3150D	500,	B3150N	500,	B5421D	500
	B6121D	370,	B6122D	180,	B6122N	180,	B7160D	300
	B7160N	300,	B0021D	550,	B0022D	550		/

DEL(P) delay from the original schedule for a second pilot (month)

/	LTJG-TOI	0,	LTJG-JOHN	1,	LTJG-ROCK	1,	ENS-SMITH	0
	ENS-HAWS	0,	CDT-POWELL	0,	CDT-SNYDER	0,	CDT-KORCAL	1
	CDT-NOVAK	0,	CDT-MCGON	0,	CDT-SIM	0		/ ;

TABLE

DAY(I,P) number of days since the last training of item I

	LTJG-TOI	LTJG-JOHN	LTJG-ROCK	ENS-SMITH	ENS-HAWS	CDT-POWELL
B2210D	100	70	50	120	370	360
B2221D	20	23	14	16	26	5
B2221N	11	18	6	4	24	13
B2222D	23	20	11	13	7	2
B2222N	16	29	39	34	56	39
B2223D	30	14	50	120	12	5
B2224D	17	25	25	13	6	20
B2224N	5	27	19	23	35	45
B2225D	12	8	50	120	8	12
B2225H	25	15	50	120	370	360
B2226D	11	8	20	45	9	11
B2231D	55	38	50	120	370	360

B2321D	36	126	50	120	35	37
B2322D	36	35	45	85	13	13
B2322N	67	79	50	11	33	44
B2323D	25	39	45	65	20	22
B2323N	5	25	19	48	13	51
B2400D	450	445	50	120	370	360
B3220D	210	180	50	120	75	90
B3220N	330	300	50	120	200	190
B3111D	150	96	20	55	7	25
B3112D	150	100	15	50	12	12
B3113D	155	75	50	28	70	110
B3114D	140	70	50	13	42	55
B3120D	5	445	50	120	370	360
B3120N	450	445	50	120	370	360
B3130D	5	445	50	120	370	360
B3130N	450	445	50	120	370	360
B3140D	450	445	50	120	370	360
B3150D	450	445	50	120	370	360
B3150N	450	450	50	120	370	360
B5421D	450	445	50	120	370	360
B6121D	20	10	50	120	370	360
B6122D	14	126	50	120	45	43
B6122N	7	98	50	120	23	12
B7160D	270	214	50	120	124	150
B7160N	240	190	50	120	97	123
B0021D	450	445	50	120	370	360
B0022D	450	445	50	120	370	360

+	CDT-SNYDER	CDT-KORCAL	CDT-NOVAK	CDT-MCGON	CDT-SIM
B2210D	350	205	190	47	46
B2221D	10	3	7	6	8
B2221N	17	16	10	9	4
B2222D	10	4	1	25	18
B2222N	48	16	45	47	46
B2223D	11	205	190	47	46
B2224D	12	21	24	5	23
B2224N	25	15	19	47	46
B2225D	12	205	190	47	46
B2225H	350	205	190	47	46
B2226D	16	15	12	47	46
B2231D	350	205	190	47	46
B2321D	44	67	55	47	46
B2322D	26	39	43	22	5
B2322N	55	109	100	47	46
B2323D	11	76	65	17	21
B2323N	43	23	4	47	46
B2400D	350	205	190	47	46
B3220D	78	9	5	47	46
B3220N	169	24	49	47	46
B3111D	30	43	42	47	46
B3112D	15	45	47	47	46
B3113D	100	15	7	47	46
B3114D	55	99	110	47	46
B3120D	360	205	190	47	46
B3120N	360	205	190	47	46
B3130D	360	205	190	47	46

B3130N	360	205	190	47	46
B3140D	360	205	190	47	46
B3150D	360	205	190	47	46
B3150N	360	205	190	47	46
B5421D	360	205	190	47	46
B6121D	360	205	190	47	46
B6122D	53	34	45	47	46
B6122N	25	7	22	47	46
B7160D	145	87	77	47	46
B7160N	110	54	45	47	46
B0021D	350	205	190	47	46
B0022D	350	205	190	47	46 ;

TABLE  
M(I,P) set of required items for a pilot P during the current month

	LTJG-TOI	LTJG-JOHN	LTJG-ROCK	ENS-SMITH	ENS-HAWS	CDT-POWELL
B2210D	0	0	0	0	0	0
B2221D	2	2	1	1	1	1
B2221N	1	1	1	1	1	1
E2222D	1	1	1	1	1	1
B2222N	1	1	0	1	1	1
B2223D	0	1	0	0	0	0
B2224D	1	1	1	1	1	1
B2224N	1	1	0	1	1	1
B2225D	1	1	0	0	0	0
B2225H	1	2	0	0	0	0
B2226D	2	1	0	1	0	0
B2231D	0	0	0	0	0	0
B2321D	0	1	0	1	0	0
B2322D	1	0	0	0	0	0
B2322N	0	1	1	0	1	1
B2323D	1	1	0	1	0	0
B2323N	1	0	0	0	1	1
B2400D	1	0	0	0	0	0
B3220D	0	0	0	1	0	0
B3220N	0	0	0	0	0	0
B3111D	0	0	0	0	0	0
B3112D	0	0	0	0	0	0
B3113D	0	0	1	0	1	1
B3114D	0	0	1	0	0	0
B3120D	3	2	0	0	0	0
B3120N	2	0	0	0	0	0
B3130D	2	1	0	0	0	0
B3130N	2	0	0	0	0	0
B3140D	1	0	0	0	0	0
B3150D	1	0	0	0	0	0
B3150N	0	0	0	0	0	0
B5421D	1	0	0	0	0	0
B6121D	0	1	0	0	0	0
B6122D	1	1	0	0	0	0
B6122N	1	1	0	0	0	0
B7160D	2	0	0	1	0	0
B7160N	1	0	0	0	0	0
B0021D	0	0	0	0	0	0
B0022D	0	0	0	0	0	0

+	CDT-SNYDER	CDT-KORCAL	CDT-NOVAK	CDT-MCGON	CDT-SIM
B2210D	0	0	0	0	0
B2221D	1	1	1	1	1
B2221N	1	1	1	1	1
B2222D	1	1	1	1	1
B2222N	1	0	0	1	1
B2223D	0	0	0	0	0
B2224D	1	1	1	1	1
B2224N	1	0	0	1	1
B2225D	0	1	1	0	0
B2225H	0	0	0	0	0
B2226D	0	1	1	1	1
B2231D	0	0	0	0	0
B2321D	0	0	0	0	0
B2322D	0	1	1	0	0
B2322N	1	0	0	0	0
B2323D	0	1	1	0	0
B2323N	1	0	0	1	1
B2400D	0	0	0	0	0
B3220D	0	0	0	0	0
B3220N	0	0	0	0	0
B3111D	0	1	1	1	1
B3112D	0	1	1	1	1
B3113D	1	0	0	0	0
B3114D	0	1	1	0	0
B3120D	0	0	0	0	0
B3120N	0	0	0	0	0
B3130D	0	0	0	0	0
B3130N	0	0	0	0	0
B3140D	0	0	0	0	0
B3150D	0	0	0	0	0
B3150N	0	0	0	0	0
B5421D	0	0	0	0	0
B6121D	0	0	0	0	0
B6122D	0	0	0	0	0
B6122N	0	1	1	0	0
B7160D	0	0	0	0	0
B7160N	0	0	0	0	0
B0021D	0	0	0	0	0
B0022D	0	0	0	0	0 ;

SCALAR

FCTR	balancing factor for the objective functions	/ 1 /
DHELO	number of flights (hops) available for day	/ 10 /
NHELO	number of flights (hops) available for night	/ 6 /
DINST	number of instructors available for day	/ 8 /
NINST	number of instructors available for night	/ 5 / ;

PARAMETER

DL(P)	delay weight (relative)
COST(I,P)	level of importance of training items for each second pilot
COSTA (P)	level of importance to reply for each second pilot ;

```

DL(P) = ( 18 + DEL(P) ) / 18 ;

COST(I,P) $( DAY(I,P) LT DBAR(I) )
           = M(I,P) * DL(P) * DAY(I,P) / DBAR(I) ;
COST(I,P) $( DAY(I,P) GE DBAR(I) )
           = M(I,P) * DL(P) * ( DAY(I,P) / DBAR(I) ) **2 ;
COSTA(P) = FCTR * T(P) ;

```

DISPLAY COST;

SETS

```

IPD(I,P)    allowable items for daytime schedule
IPN(I,P)    allowable items for nighttime schedule ;

```

```

IPD(I,P) = YES $ ( M(I,P) $ DY(I) EQ 1 ) ;
IPN(I,P) = YES $ ( M(I,P) $ NITE(I) EQ 1 ) ;

```

BINARY VARIABLES

```

X(I,P)    one if pilot P performs item I otherwise zero

Y(P)      one if pilot P flies on that day otherwise zero ;

```

VARIABLES

```

PROFT      schedule MOE ;

```

EQUATIONS

```

DOBJ      objective function of daytime schedule
DHOURL(P) maximum flight hours for each second pilot
DITEM(P)  maximum items for each flight
DCOMP(I,P) items are always completed by flight
DHOPINST  aircraft and instructor availability

NOCBJ     objective function of night schedule
NHOURL(P) maximum flight hours for each second pilot (night)
NITEM(P)  maximum items for each flight
NCOMP(I,P) items are always finished by flight
NHOPINST  aircraft and instructor availability ;

```

\* daytime scheduling model

\* maximize

```

DOBJ..      PROFT =E= SUM((I,P), COST(I,P) * X(I,P) $ IPD(I,P))
              + SUM( P, COSTA(P) * Y(P)) ;

```

\* subject to

```

DHOURL(P).. SUM(I, H(I) * X(I,P) $ IPD(I,P)) =L= HBARD(P) ;
DITEM(P)..  SUM(I, X(I,P) $ IPD(I,P))          =L= IBAR(P) ;
DHOPINST..  SUM(P, Y(P))                       =L= MIN(DHELO, DINST) ;
DCOMP(I,P).. X(I,P) $ IPD(I,P) - Y(P)         =L= 0 ;

```

\* nighttime scheduling model

\* maximize

```

NOBJ..      PROFT =E= SUM((I,P), COST(I,P) * X(I,P) $ IPN(I,P))
              + SUM( P, COSTA(P) * Y(P)) ;

```

```

* subject to
NHOURL(P)..    SUM(I, H(I) * X(I,P) $ IPN(I,P)) =L= HBARN(P)          ;
NITEM(P)..    SUM(I, X(I,P) $ IPN(I,P))          =L= IBAR(P)          ;
NHOPINST..    SUM(P, Y(P))                        =L= MIN(NHELO, NINST) ;
NCOMP(I,P)..  X(I,P) $ IPN(I,P) - Y(P)          =L= 0                  ;

MODEL CPDAY    second pilot daytime model
               / DHOURL, DITEM, DHOPINST, DCOMP, DOBJ /
  CPNGT        second pilot night model
               / NHOURL, NITEM, NHOPINST, NCOMP, NOBJ / ;

SOLVE CPDAY USING MIP MAXIMIZING PROFIT;

PARAMETER
  TRAINING(I,P)  scheduled second pilots and items for daytime
  HAPPYGUY(P)    scheduled second pilots          ;
                TRAINING(I,P) = X.L(I,P) ;
                HAPPYGUY(P)   = Y.L(P)   ;

DISPLAY TRAINING ;
DISPLAY HAPPYGUY ;

SOLVE CPNGT USING MIP MAXIMIZING PROFIT;

PARAMETER
  DOIT(I,P)     scheduled second pilots and items for night
  FLYTHEM(P)    scheduled second pilots          ;
                DOIT(I,P)   = X.L(I,P) $ IPN(I,P) ;
                FLYTHEM(P) = Y.L(P) $ ( SUM ( I, X.L(I,P) $ IPN(I,P))) ;

DISPLAY DOIT    ;
DISPLAY FLYTHEM ;

```

## APPENDIX C.

### *GAMS program listing of the Trainee model for the USMC*

```
$TITLE MODEL 3 (TRAINEES) - USMC
$OFFUPPER OFFSYMXREF OFFSYMLIST
OPTIONS SOLPRINT = Off
OPTIONS LIMCOL = 0 , LIMROW = 0
```

- \* An integer programming model for flight training scheduling in the USMC.
- \* Daily flight schedule for trainees in combat capable training course
- \* will be solved.
- \* The items for tomorrow will be selected from the allowable set of items,
- \* and qualified instructors will be paired,
- \* subject to both instructor and flight hours ( aircraft ) availability.
- \* MOE of the model is keep the students on schedule.
- \* Part of data sets are obtained FRS HMT-303, USMC, Camp Pendleton, CA.

#### SETS

```
I items of syllabus (34)
  / FAM100, FAM101, FAM102, FAM103, FAM104, FAM105
    FAM106, FAM107, FAM108, FAM109, FAM110, FAM111
    INS120, INS121, INS122, INS123, INS124, INS125
    FOM130, FOM131, FOM132, TEF140, NAV150, NAV151
    NAV152, ATG160, ATG161, ATG162, TAC170, TAC171
    NVG180, NVG181, NVG182, CCX190 /

P student pilots (11)
  / DARLING, SHEERIN, STEININGER, PANTEN, HENSEL, MILNE
    ADAMS, ROSENTL, EAGLE, READ, KANG /

Q instructors (15)
  / GULMAN, CARPENTER, WEIGL, CASTEEL, HALL, KOLB
    WEST, SCHLESINGR, FORD, JONES, HENDRICK, OWENS
    GRACE, EMERY, ORNER / ;
```

#### PARAMETERS

```
HBAR(Q) maximum flight hours per day for instructor Q
  / GULMAN 3, CARPENTER 0, WEIGL 0, CASTEEL 2
    HALL 4, KOLB 0, WEST 1.5, SCHLESINGR 3
    FORD 4, JONES 3, HENDRICK 2, OWENS 3
    GRACE 4, EMERY 1, ORNER 2 /

H(I) training time that is needed for item I
  / FAM100 1.5, FAM101 1.5, FAM102 1.5, FAM103 2.0, FAM104 2.0
    FAM105 2.0, FAM106 2.0, FAM107 2.0, FAM108 2.0, FAM109 1.5
    FAM110 1.5, FAM111 2.0, INS120 1.5, INS121 1.5, INS122 1.5
    INS123 2.0, INS124 2.0, INS125 1.5, FOM130 1.0, FOM131 1.0
    FOM132 1.0, TEF140 1.5, NAV150 1.5, NAV151 1.5, NAV152 1.5
    ATG160 1.5, ATG161 1.5, ATG162 1.5, TAC170 1.5, TAC171 1.5
    NVG180 1.5, NVG181 1.5, NVG182 1.5, CCX190 2.0 /
```

IBAR(P) maximum number of training items per day for pilot P  
 / DARLING 2, SHEERIN 2, STEININGER 2,  
 PANTEN 2, HENSEL 2, MILNE 2, ADAMS 2  
 ROSENTL 2, EAGLE 2, READ 2, KANG 2 /

DHAT(P) number of days that pilot P has been assigned for training  
 / DARLING 42, SHEERIN 42, STEININGER 42,  
 PANTEN 70, HENSEL 42, MILNE 70, ADAMS 70  
 ROSENTL 7, EAGLE 7, READ 7, KANG 7 /

NC(P) actual number of finished items since the assignment of pilot P  
 / DARLING 11, SHEERIN 12, STEININGER 17,  
 PANTEN 23, HENSEL 11, MILNE 21, ADAMS 9  
 ROSENTL 1, EAGLE 2, READ 0, KANG 1 / ;

TABLE

QUAL(I,Q) qualification of instructor to teach item I

	GULMAN	CARPENTER	WEIGL	CASTEEL	HALL	KOLB	WEST	SCHLESINGR
FAM100	1	1	1	1	1	1	1	1
FAM101	1	1	1	1	1	1	1	1
FAM102	1	1	1	1	1	1	1	1
FAM103	1	1	1	1	1	1	1	1
FAM104	1	1	1	1	1	1	1	1
FAM105	1	1	1	1	1	1	1	1
FAM106	1	1	1	1	1	1	1	1
FAM107	1	1	1	1	1	1	1	1
FAM108	1	1	1	1	1	1	1	1
FAM109	1	1	1	1	1	1	1	1
FAM110	1	1	1	1	1	1	1	1
FAM111	1	1	1	1	1	1	1	1
INS120	1	1	1	1	1	1	1	1
INS121	1	1	1	1	1	1	1	1
INS122	1	1	1	1	1	1	1	1
INS123	1	1	1	1	1	1	1	1
INS124	1	1	1	1	1	1	1	1
INS125	1	1	1	1	1	1	1	1
FOM130	1	1	1	0	1	1	1	1
FOM131	1	1	1	0	1	1	1	1
FOM132	1	1	1	0	1	1	1	1
TEF140	1	1	1	1	1	1	1	1
NAV150	1	1	1	1	1	1	1	1
NAV151	1	1	1	1	1	1	1	1
NAV152	1	1	1	1	1	1	1	1
ATG160	1	1	1	1	1	1	1	1
ATG161	1	1	1	1	1	1	1	1
ATG162	1	1	1	1	1	1	1	1
TAC170	1	1	1	1	1	1	1	1
TAC171	1	1	1	1	1	1	1	1
NVG180	1	0	1	1	0	1	1	1
NVG181	1	0	1	1	0	1	1	1
NVG182	1	0	1	1	0	1	1	1
CCX190	1	0	1	1	0	1	1	1

+	FORD	JONES	HENDRICK	OWENS	GRACE	EMERY	ORNER
FAM100	1	1	1	1	1	0	1
FAM101	1	1	1	1	1	0	1
FAM102	1	1	1	1	1	0	1
FAM103	1	1	1	1	1	0	1
FAM104	1	1	1	1	1	0	1
FAM105	1	1	1	1	1	0	1
FAM106	1	1	1	1	1	0	1
FAM107	1	1	1	1	1	0	1
FAM108	1	1	1	1	1	0	1
FAM109	1	1	1	1	1	0	1
FAM110	1	1	1	1	1	0	1
FAM111	1	1	1	1	1	0	1
INS120	1	1	1	1	1	1	1
INS121	1	1	1	1	1	1	1
INS122	1	1	1	1	1	1	1
INS123	1	1	1	1	1	1	1
INS124	1	1	1	1	1	1	1
INS125	1	1	1	1	1	1	1
FOM130	1	1	1	1	1	1	1
FOM131	1	1	1	1	1	1	1
FOM132	1	1	1	1	1	1	1
TEF140	1	1	1	1	1	0	1
NAV150	0	1	1	1	1	0	1
NAV151	0	1	1	1	1	0	1
NAV152	0	1	1	1	1	0	1
ATG160	1	1	1	1	1	0	1
ATG161	1	1	1	1	1	0	1
ATG162	1	1	1	1	1	0	1
TAC170	1	1	1	1	1	0	1
TAC171	1	1	1	1	1	0	1
NVG180	1	1	1	1	1	0	1
NVG181	1	1	1	1	1	0	1
NVG182	1	1	1	1	1	0	1
CCX190	1	1	1	1	1	0	1 ;

TABLE  
 PROG(I,P) completed items I for student pilot P

	DARLING	SHEERIN	STEININGER	PANTEN	HENSEL	MILNE	ADAMS
FAM100	1	1	1	1	1	1	1
FAM101	1	1	1	1	1	1	1
FAM102	1	1	1	1	1	1	1
FAM103	1	1	1	1	1	1	1
FAM104	1	1	1	1	1	1	1
FAM105	1	1	1	1	1	1	1
FAM106	1	1	1	1	0	1	0
FAM107	0	1	1	1	0	1	0
FAM108	0	1	1	1	0	1	0
FAM109	0	0	1	1	0	1	0
FAM110	0	0	0	1	0	1	0
FAM111	0	0	0	1	0	0	0
INS120	1	1	1	1	1	1	0
INS121	0	1	1	1	1	1	0
INS122	1	0	1	0	1	1	0
INS123	0	0	0	0	1	0	0

INS124	0	0	0	1	0	0	0
INS125	0	0	0	0	0	0	0
FOM130	0	0	0	0	0	0	0
FOM131	0	0	0	0	0	0	0
FOM132	0	0	0	0	0	0	0
TEF140	1	0	1	1	0	1	0
NAV150	1	0	1	1	1	1	0
NAV151	0	1	1	1	0	1	0
NAV152	0	0	1	0	0	0	0
ATG160	0	0	0	1	0	1	1
ATG161	0	0	0	1	0	1	1
ATG162	0	0	0	1	0	1	0
TAC170	0	0	0	0	0	0	0
TAC171	0	0	0	0	0	0	0
NVG180	0	0	0	1	0	1	0
NVG181	0	0	0	1	0	0	0
NVG182	0	0	0	0	0	0	0
CCX190	0	0	0	0	0	0	0

+	ROSENTL	EAGLE	READ	KANG
FAM100	1	1	0	1
FAM101	0	1	0	0
FAM102	0	0	0	0
FAM103	0	0	0	0
FAM104	0	0	0	0
FAM105	0	0	0	0
FAM106	0	0	0	0
FAM107	0	0	0	0
FAM108	0	0	0	0
FAM109	0	0	0	0
FAM110	0	0	0	0
FAM111	0	0	0	0
INS120	0	0	0	0
INS121	0	0	0	0
INS122	0	0	0	0
INS123	0	0	0	0
INS124	0	0	0	0
INS125	0	0	0	0
FOM130	0	0	0	0
FOM131	0	0	0	0
FOM132	0	0	0	0
TEF140	0	0	0	0
NAV150	0	0	0	0
NAV151	0	0	0	0
NAV152	0	0	0	0
ATG160	0	0	0	0
ATG161	0	0	0	0
ATG162	0	0	0	0
TAC170	0	0	0	0
TAC171	0	0	0	0
NVG180	0	0	0	0
NVG181	0	0	0	0
NVG182	0	0	0	0
CCX190	0	0	0	0 ;

ALIAS(I,J);

TABLE

PREREQ(I,J) item I is prerequisite for item J

	FAM100	FAM101	FAM102	FAM103	FAM104	FAM105	FAM106	FAM107
FAM100	0	1	1	1	1	1	1	1
FAM101	0	0	1	1	1	1	1	1
FAM102	0	0	0	1	1	1	1	1
FAM103	0	0	0	0	1	1	1	1
FAM104	0	0	0	0	0	1	1	1
FAM105	0	0	0	0	0	0	1	1
FAM106	0	0	0	0	0	0	0	1
FAM107	0	0	0	0	0	0	0	0
FAM108	0	0	0	0	0	0	0	0
FAM109	0	0	0	0	0	0	0	0
FAM110	0	0	0	0	0	0	0	0
FAM111	0	0	0	0	0	0	0	0
INS120	0	0	0	0	0	0	0	0
INS121	0	0	0	0	0	0	0	0
INS122	0	0	0	0	0	0	0	0
INS123	0	0	0	0	0	0	0	0
INS124	0	0	0	0	0	0	0	0
INS125	0	0	0	0	0	0	0	0
FOM130	0	0	0	0	0	0	0	0
FOM131	0	0	0	0	0	0	0	0
FOM132	0	0	0	0	0	0	0	0
TEF140	0	0	0	0	0	0	0	0
NAV150	0	0	0	0	0	0	0	0
NAV151	0	0	0	0	0	0	0	0
NAV152	0	0	0	0	0	0	0	0
ATG160	0	0	0	0	0	0	0	0
ATG161	0	0	0	0	0	0	0	0
ATG162	0	0	0	0	0	0	0	0
TAC170	0	0	0	0	0	0	0	0
TAC171	0	0	0	0	0	0	0	0
NVG180	0	0	0	0	0	0	0	0
NVG181	0	0	0	0	0	0	0	0
NVG182	0	0	0	0	0	0	0	0
CCX190	0	0	0	0	0	0	0	0

+	FAM108	FAM109	FAM110	FAM111	INS120	INS121	INS122	INS123
FAM100	1	1	1	1	1	1	1	1
FAM101	1	1	1	1	1	1	1	1
FAM102	1	1	1	1	1	1	1	1
FAM103	1	1	1	1	1	1	1	1
FAM104	1	1	1	1	1	1	1	1
FAM105	1	1	1	1	0	0	0	0
FAM106	1	1	1	1	0	0	0	0
FAM107	1	1	1	1	0	0	0	0
FAM108	0	1	1	1	0	0	0	0
FAM109	0	0	1	1	0	0	0	0
FAM110	0	0	0	1	0	0	0	0
FAM111	0	0	0	0	0	0	0	0
INS120	0	0	0	0	0	1	0	1
INS121	0	0	0	0	0	0	0	0

INS122	0	0	0	0	0	0	0	0
INS123	0	0	0	0	0	0	0	0
INS124	0	0	0	0	0	0	0	0
INS125	0	0	0	0	0	0	0	0
FOM130	0	0	0	0	0	0	0	0
FOM131	0	0	0	0	0	0	0	0
FOM132	0	0	0	0	0	0	0	0
TEF140	0	0	0	0	0	0	0	0
NAV150	0	0	0	0	0	0	0	0
NAV151	0	0	0	0	0	0	0	0
NAV152	0	0	0	0	0	0	0	0
ATG160	0	0	0	0	0	0	0	0
ATG161	0	0	0	0	0	0	0	0
ATG162	0	0	0	0	0	0	0	0
TAC170	0	0	0	0	0	0	0	0
TAC171	0	0	0	0	0	0	0	0
NVG180	0	0	0	0	0	0	0	0
NVG181	0	0	0	0	0	0	0	0
NVG182	0	0	0	0	0	0	0	0
CCX190	0	0	0	0	0	0	0	0

+	INS124	INS125	FOM130	FOM131	FOM132	TEF140	NAV150	NAV151
FAM100	1	1	1	1	1	1	1	1
FAM101	1	1	1	1	1	1	1	1
FAM102	1	1	1	1	1	1	1	1
FAM103	1	1	1	1	1	1	1	1
FAM104	1	1	1	1	1	1	1	1
FAM105	0	0	0	0	0	0	0	0
FAM106	0	0	0	0	0	0	0	0
FAM107	0	0	0	0	0	0	0	0
FAM108	0	0	0	0	0	0	0	0
FAM109	0	0	0	0	1	0	0	0
FAM110	0	0	0	0	1	0	0	0
FAM111	0	0	0	0	0	0	0	0
INS120	1	1	0	0	0	0	0	0
INS121	0	1	0	0	0	0	0	0
INS122	0	1	0	0	0	0	0	0
INS123	0	1	0	0	0	0	0	0
INS124	0	1	0	0	0	0	0	0
INS125	0	0	0	0	0	0	0	0
FOM130	0	0	0	1	1	1	0	0
FOM131	0	0	0	0	1	1	0	0
FOM132	0	0	0	0	0	1	0	0
TEF140	0	0	0	0	0	1	0	0
NAV150	0	0	0	0	0	0	0	0
NAV151	0	0	0	0	0	0	0	0
NAV152	0	0	0	0	0	0	0	0
ATG160	0	0	0	0	0	0	0	0
ATG161	0	0	0	0	0	0	0	0
ATG162	0	0	0	0	0	0	0	0
TAC170	0	0	0	0	0	0	0	0
TAC171	0	0	0	0	0	0	0	0
NVG180	0	0	0	0	0	0	0	0
NVG181	0	0	0	0	0	0	0	0
NVG182	0	0	0	0	0	0	0	0
CCX190	0	0	0	0	0	0	0	0

+	NAV152	ATG160	ATG161	ATG162	TAC170	TAC171	NVG180	NVG181
FAM100	1	1	1	1	1	1	1	1
FAM101	1	1	1	1	1	1	1	1
FAM102	1	1	1	1	1	1	1	1
FAM103	1	1	1	1	1	1	1	1
FAM104	1	1	1	1	1	1	1	1
FAM105	0	0	0	0	0	0	0	0
FAM106	0	1	1	1	1	1	0	0
FAM107	0	0	0	0	0	0	0	0
FAM108	0	0	0	0	0	0	0	0
FAM109	0	0	0	0	0	0	1	1
FAM110	0	0	0	0	0	0	1	1
FAM111	0	0	0	0	0	0	0	0
INS120	0	0	0	0	0	0	0	0
INS121	0	0	0	0	0	0	0	0
INS122	0	0	0	0	0	0	0	0
INS123	0	0	0	0	0	0	0	0
INS124	0	0	0	0	0	0	0	0
INS125	0	0	0	0	0	0	0	0
FOM130	0	0	0	0	0	0	0	0
FOM131	0	0	0	0	0	0	0	0
FOM132	0	0	0	0	0	0	0	0
TEF140	0	1	1	1	0	0	0	0
NAV150	1	0	0	0	0	0	1	1
NAV151	1	0	0	0	0	0	0	0
NAV152	0	0	0	0	0	0	0	0
ATG160	0	0	1	1	1	1	0	0
ATG161	0	0	0	1	1	1	0	0
ATG162	0	0	0	0	1	1	0	0
TAC170	0	0	0	0	0	1	0	0
TAC171	0	0	0	0	0	0	0	0
NVG180	0	0	0	0	0	0	0	0
NVG181	0	0	0	0	0	0	0	0
NVG182	0	0	0	0	0	0	0	0
CCX190	0	0	0	0	0	0	0	0

+	NVG182	CCX190
FAM100	1	1
FAM101	1	1
FAM102	1	1
FAM103	1	1
FAM104	1	1
FAM105	0	1
FAM106	0	1
FAM107	0	1
FAM108	0	1
FAM109	1	1
FAM110	0	1
FAM111	0	1
INS120	0	1
INS121	0	1
INS122	0	1
INS123	0	1
INS124	0	1
INS125	0	1
FOM130	0	1

FOM131	0	1
FOM132	0	1
TEF140	0	1
NAV150	1	1
NAV151	0	1
NAV152	0	1
ATG160	0	1
ATG161	0	1
ATG162	0	1
TAC170	0	1
TAC171	0	1
NVG180	0	1
NVG181	0	1
NVG182	0	1
CCX190	0	0

SCALAR

NTOTAL	total number of syllabus items in the course	/ 34 /
DTOTAL	total number of days pilot is allowed for training	/ 140 /
CPRIME	weight for penalty variable Z	/ 1 /
FTHR	flight hours goal on a day T	/ 24 / ;

\* for prerequisite requirements

PARAMETER

REQ(I,J,P) set of prerequisites I to perform item J for pilot P  
 SATF(I,J,P) completed set of items by pilot P  
 UNST(I,J,P) uncompleted set of prerequisites I for item J by pilot P  
 POSSB(I,P) allowable items or completed items by pilot P  
 ALLOW(I,P) allowable items for pilot P  
 POSSI(I,P) potentially allowable items or completed items by pilot P  
 PALLOW(I,P) items exactly one prerequisite remaining for pilot P ;

\* expand prerequisites. every student has to do item I before item J  
 $REQ(I,J,P) = 1 \text{ } \$ \text{ } ( PREREQ(I,J) EQ 1 ) ;$

\* student P has done item I  
 $SATF(I,J,P) = 1 \text{ } \$ \text{ } ( PROG(I,P) EQ 1 ) ;$

\* a student P has an remaining item J and prerequisite I has not yet done  
 $UNST(I,J,P) = 1 \text{ } \$ \text{ } (( REQ(I,J,P) - SATF(I,J,P) ) EQ 1 ) ;$

\* a set of prerequisites for item J has been done (no prerequisite remaining)  
 $POSSB(J,P) = 1 \text{ } \$ \text{ } (( SUM ( I, UNST(I,J,P) )) EQ 0 ) ;$

\* a student P has exactly one prerequisite remaining to do item J  
 $POSSI(J,P) = 1 \text{ } \$ \text{ } (( SUM ( I, UNST(I,J,P) )) EQ 1 ) ;$

\* a student P can perform item I but has not yet done  
 $ALLOW(I,P) = 1 \text{ } \$ \text{ } (( POSSB(I,P) - PROG(I,P)) EQ 1 ) ;$

\* a student P can do item I if one remaining prerequisite were done  
 $PALLOW(I,P) = 1 \text{ } \$ \text{ } (( POSSI(I,P) - PROG(I,P)) EQ 1 ) ;$

\* ALLOW is a set of items that a student P can do, and PALLOW is potentially allowable items if remaining prerequisite were done as a first item of a day

```

SET  IA(I,P)    allowable item indices for student P
     IB(I,P,Q)  allowable item indices for student and for instructor
     IE(I,P)    potentially allowable item indices for items and for student P
     IC(I,P,Q)  potentially allowable item indices for I for P and for Q
     IP(I,P)    union of IA and IE
     IQ(I,P,Q)  union of IB and IC
     ID(I,P)    daytime formation items
     IN(I,P)    nighttime formation item ;

```

```

IA( I , P ) = YES $ ( ALLOW(I,P) EQ 1 ) ;

```

```

IE( I , P ) = YES $ ( PALLOW(I,P) EQ 1 ) ;

```

```

IB(I, P, Q)= YES $ (( ALLOW(I,P) EQ 1 )
                    AND ( QUAL(I,Q) EQ 1 )
                    AND ( HBAR(Q) NE 0 ) ) ;

```

```

IC(I, P, Q)= YES $ (( PALLOW(I,P) EQ 1 )
                    AND ( QUAL(I,Q) EQ 1 )
                    AND ( HBAR(Q) NE 0 ) );

```

```

IP(I,P)      = IA(I,P) + IE(I,P) ;

```

```

IQ(I,P,Q)    = IB(I,P,Q) + IC(I,P,Q) ;

```

```

ID('FOM130', P ) = YES ;

```

```

ID('FOM131', P ) = YES ;

```

```

IN('FOM132', P ) = YES ;

```

```

DISPLAY IA ;
DISPLAY IE ;
DISPLAY IP ;

```

#### PARAMETER

```

COST(P)      C sup 1 sub p t

```

```

COSTT(P)     C sup 2 sub p t

```

```

CDF(P)       C prime sub p t

```

```

NHAT(P)      number of items which should have been completed ;

```

```

NHAT(P) = 1.35 * NTOTAL * DHAT(P) / DTOTAL ;

```

```

COST(P) = ( 1 + MAX ( 0, NHAT(P) - NC(P) ) ) ** 2 ;

```

```

COSTT(P) = ( 1 + MAX ( 0, NHAT(P) - ( NC(P) + 1 ) ) ) ** 2 ;

```

```

CDF(P) = COST(P) - COSTT(P) ;

```

```

DISPLAY COST ;
DISPLAY COSTT;
DISPLAY CDF ;

```

#### BINARY VARIABLES

```

X(I,P)       one if student P performs item I otherwise zero

```

```

Y(I,P,Q)     one if inst Q teaches student P on item I otherwise zero

```

```

W(P)         one if student P flies item I as a second item ;

```

#### INTEGER VARIABLE

```

V            daytime formation organizer

```

```

VV          nighttime formation organizer ;

```

POSITIVE VARIABLE

ZP           overachievement for flight hours goal  
 ZM           underachievement for flight hours goal ;

VARIABLE

PROFT           schedule MOE ;

EQUATIONS

OBJ           objective function of schedule  
 SQHR          total flight hours goal constraint for squadron  
 ASSGN(I,P)   assignment of instructor Q to student P if P flies  
 INST(Q)       limits availability of instructor pilot Q  
 ITEM(P)       maximum number of items per day  
 PREQ(I,J,P)   enforces prerequisite relationships  
 LIMTWO(P)     students can be flown at most two items  
 DFORM         pairs up daytime formation items  
 NFORM         pairs up nighttime formation items ;

\* maximize

\* (modified objective function)

OBJ..       PROFT =E=   SUM ((I, P), COST(P)\*X(I,P) \$ IA(I,P))  
                           + SUM ((I, P), COSTT(P) \* X(I,P) \$ IE(I,P))  
                           - CPRIME \*(ZP + ZM)                   ;

\* (original objective function)

\*OBJ..       PROFT =E=   SUM ((I, P), COST(P) \* X(I,P) \$ IP(I,P))  
 \*                           - CPRIME \*(ZP + ZM)                   ;  
 \*                           - SUM ( P, CDF(P) \* W(P) )       ;

\*subject to

SQHR..               SUM( (I,P), H(I) \* (X(I,P) \$ IP(I,P)) ) - ZP + ZM  
 =E= FTHR       ;

ASSGN(I,P)..       SUM( Q, Y(I,P,Q) \$ IQ(I,P,Q) ) - X(I,P) \$ IP(I,P)  
 =E= 0           ;

INST(Q)..           SUM( (I,P), H(I) \* (Y(I,P,Q) \$ IQ(I,P,Q)) )  
 =L= HBAR(Q)   ;

ITEM(P)..           SUM( I, X(I,P) \$ IP(I,P) )  
 =L= IBAR(P)   ;

PREQ(I,J,P)..       (X(J,P) - X(I,P)) \$ (( ALLOW(I,P) EQ 1 )  
   AND ( PALLOW(J,P) EQ 1 )  
   AND ( PREREQ(I,J) EQ 1 ) )  
 =L= 0       ;

LIMTWO(P)..       SUM ( I , X(I,P) \$ IP(I,P)) - W(P)  
 =L= 1       ;

DFORM..           SUM ((I,P), X(I,P) \$ ID(I,P)) - 2 \* V  
 =E= 0       ;

NFORM..           SUM ((I,P), X(I,P) \$ IN(I,P)) - 2 \* VV  
 =E= 0       ;

MODEL USMC /ALL/ ;

SOLVE USMC USING MIP MAXIMIZING PROFIT;

PARAMETER

TRAINING(I,P) Items and Students  
SECOND(I,P) exclusive second item  
TEACHER(I,P,Q) Items - Students and Instructors ;  
TRAINING(I,P) = X.L(I,P) \$ IP(I,P) ;  
SECOND(I,P) = X.L(I,P) \$ IE(I,P) ;  
TEACHER(I,P,Q) = Y.L(I,P,Q) \$ IQ(I,P,Q) ;

\* print out the solution in a tabular format

DISPLAY TRAINING ;  
DISPLAY SECOND ;  
DISPLAY TEACHER ;

DISPLAY ZP.L ;  
DISPLAY ZM.L ;  
DISPLAY V.L ;  
DISPLAY VV.L ;  
DISPLAY W.L ;

## APPENDIX D.

### *Modification of the USMC model*

--- add sets and parameters below ---

SETS

TERF(I) / TEF140 /  
 NIGHT(I) / FAM109, FAM110, FOM132, NVG180, NVG181, NVG182 / ;

PARAMETER

WW(I) weight of items

/ FAM100 2.5,	FAM101 2.5,	FAM102 2.5,	FAM103 2.5,	FAM104 2.5
FAM105 2.0,	FAM106 2.0,	FAM107 2.0,	FAM108 2.0,	FAM109 1.9
FAM110 1.9,	FAM111 1.8,	INS120 1.5,	INS121 1.4,	INS122 1.5
INS123 1.4,	INS124 1.4,	INS125 1.4,	FOM130 1.0,	FOM131 1.0
FOM132 0.9,	TEF140 1.5,	NAV150 1.7,	NAV151 1.6,	NAV152 1.6
ATG160 1.3,	ATG161 1.3,	ATG162 1.3,	TAC170 1.2,	TAC171 1.2
NVG180 1.5,	NVG181 1.5,	NVG182 1.5,	CCX190 1.0	/ ;

TABLE

L(P,Q) number of flights for student P with instructor Q ;

	GULMAN	CARPENTER	WEIGL	CASTEEL	HALL	KOLB
DARLING	1	1	2	0	0	1
SHEERIN	1	0	0	1	1	2
STEININGER	1	1	0	1	1	1
PANTEN	1	2	1	1	2	2
HENSEL	0	0	0	1	1	1
MILNE	1	1	1	2	2	0
ADAMS	2	1	1	1	0	0
ROSENTL	0	0	0	0	0	0
EAGLE	0	1	0	1	0	0
READ	0	0	0	0	0	0
KANG	0	0	0	0	0	0

+	WEST	SCHLESINGR	FORD	JONES	HENDRICK	OWENS
DARLING	1	0	0	0	2	1
SHEERIN	2	1	1	1	0	0
STEININGER	2	3	1	0	1	0
PANTEN	3	1	1	2	2	1
HENSEL	1	0	2	2	1	1
MILNE	0	2	2	1	3	0
ADAMS	0	0	0	2	1	1
ROSENTL	0	0	0	0	0	0
EAGLE	0	0	0	0	0	0
READ	0	0	0	0	0	0
KANG	0	0	0	0	0	0

+	GRACE	EMERY	ORNER
DARLING	0	1	1
SHEERIN	0	1	1
STEININGER	2	2	1

PANTEN	2	1	1
HENSEL	0	0	1
MILNE	0	2	4
ADAMS	0	0	0
ROSENTL	0	0	1
EAGLE	0	0	0
READ	0	0	0
KANG	0	1	0

PARAMETER

LSN(P,Q) exposure factor of student P to instructor Q ;  
 $LSN(P,Q) = 1 / (.5 + L(P,Q)) ;$

DISPLAY LSN;

PARAMETER

CURR(I,Q) currency of instructor Q for flights, night and Terf (days);

CURR( I, 'GULMAN' )	= 1 ;
CURR( I, 'CARPENTER' )	= 1 ;
CURR( I, 'WEIGL' )	= 5 ;
CURR( I, 'CASTEEL' )	= 1 ;
CURR( I, 'HALL' )	= 1 ;
CURR( I, 'KOLB' )	= 1 ;
CURR( I, 'WEST' )	= 3 ;
CURR( I, 'SCHLESINGR' )	= 1 ;
CURR( I, 'FORD' )	= 3 ;
CURR( I, 'JONES' )	= 1 ;
CURR( I, 'HENDRICK' )	= 1 ;
CURR( I, 'OWENS' )	= 1 ;
CURR( I, 'GRACE' )	= 1 ;
CURR( I, 'EMERY' )	= 3 ;
CURR( I, 'ORNER' )	= 1 ;
CURR( NIGHT(I), 'GULMAN' )	= 10 ;
CURR( NIGHT(I), 'CARPENTER' )	= 5 ;
CURR( NIGHT(I), 'WEIGL' )	= 5 ;
CURR( NIGHT(I), 'CASTEEL' )	= 3 ;
CURR( NIGHT(I), 'HALL' )	= 10 ;
CURR( NIGHT(I), 'KOLB' )	= 5 ;
CURR( NIGHT(I), 'WEST' )	= 3 ;
CURR( NIGHT(I), 'SCHLESINGR' )	= 10 ;
CURR( NIGHT(I), 'FORD' )	= 3 ;
CURR( NIGHT(I), 'JONES' )	= 13 ;
CURR( NIGHT(I), 'HENDRICK' )	= 10 ;
CURR( NIGHT(I), 'OWENS' )	= 5 ;
CURR( NIGHT(I), 'GRACE' )	= 3 ;
CURR( NIGHT(I), 'EMERY' )	= 13 ;
CURR( NIGHT(I), 'ORNER' )	= 10 ;
CURR( TERF(I), 'GULMAN' )	= 11 ;
CURR( TERF(I), 'CARPENTER' )	= 30 ;
CURR( TERF(I), 'WEIGL' )	= 21 ;
CURR( TERF(I), 'CASTEEL' )	= 5 ;
CURR( TERF(I), 'HALL' )	= 11 ;
CURR( TERF(I), 'KOLB' )	= 21 ;
CURR( TERF(I), 'WEST' )	= 5 ;

```

CURR( TERF(I), 'SCHLESINGR') = 33 ;
CURR( TERF(I), 'FORD' )      = 24 ;
CURR( TERF(I), 'JONES' )     = 33 ;
CURR( TERF(I), 'HENDRICK' )  = 30 ;
CURR( TERF(I), 'OWENS' )     = 15 ;
CURR( TERF(I), 'GRACE' )     = 24 ;
CURR( TERF(I), 'EMERY' )     = 30 ;
CURR( TERF(I), 'ORNER' )     = 15 ;

```

---- replace the parameters below ----

```

PARAMETER
COST(I,P)  C sup 1 sub i p t
COSTT(I,P) C sup 2 sub i p t
NHAT(P)    number of items which should have been completed ;

      NHAT(P)    = 1.35 * NTOTAL * DHAT(P) / DTOTAL ;
      COST(I,P)  = WW(I) *
                  ( 1 + MAX ( 0, NHAT(P) - NC(P) ) ) ** 2 ;
      COSTT(I,P) = WW(I) *
                  ( 1 + MAX ( 0, NHAT(P) - ( NC(P) + 1 ) ) ) ** 2 ;
* assign zero cost if item i is not allowable
      COST(I,P) $ ( NOT IP(I,P) ) = 0 ;
      COSTT(I,P) $ ( NCT IP(I,P) ) = 0 ;

DISPLAY  COST ;
DISPLAY  COSTT;

```

--- replace objective function and add two sets of constraints ---

```

EQUATIONS
OBJ          objective function of schedule (replace)
SPAIR(P)    student pairing (add)
IPAIR(Q)    instructor pairing (add) ;

* maximize
OBJ..  PROFIT =E=  SUM ((I, P), COST(I,P)*X(I,P) $ IA(I,P))
                + SUM ((I, P), COSTT(I,P)*X(I,P) $ IE(I,P))
                + SUM ((I,P,Q), CURR(I,Q)*Y(I,P,Q) $ IQ(I,P,Q))
                + SUM ((I,P,Q), LSN(P,Q)*Y(I,P,Q) $ IQ(I,P,Q))
                - CPRIME *(ZP + ZM) ;

* subject to
SPAIR(P)..  X('FOM130',P) + X('FOM131',P) =L= 1 ;

IPAIR(Q)..  SUM ((I,P), Y(I,P,Q) $ ID(I,P)) =L= 1 ;

```

---The rest of the program is the same as in appendix C. ---

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