Flight Scheduling for the SH-60J Military Helicopter

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ABSTRACT

This paper deals with the flight scheduling of a patrol helicopter of the Japan Maritime Self-Defense Force (JMSDF) using a mixed-integer programming formulation. Rotary-wing aircraft SH-60J plays an important role in antisubmarine warfare (ASW) operations and naval convoys. The scheduling of the SH-60J's flight is usually done manually in many Air wings. The scheduling staffs spend a great deal of time to achieve a fair and feasible schedule. We propose a mixed-integer programming method to handle the complicated issue of scheduling and ease the staff's workload for a one-week schedule. We introduce a sequential scheduling, consisting of some elemental schedulings, to assign crews to available flights for skill training, emergency readiness, skill maintenance, and duty of instructors of the skill-training courses.

INTRODUCTION

Scheduling is necessary to effectively carry out human activities in the commercial and military worlds. If we limit the scheduling to the routing or crew scheduling of vehicles, the scheduling technique is applied to a variety of problems in the real world.

The scheduling problem of commercial airlines has been studied since the 1990s (Walker 1992). There are many types of scheduling problems for airplanes. The aircraft routing problem (Sarac et al. 2006) aims to assign a specific airplane to a permissive type of airplane and to determine the airplane's flight schedule in the long term, including the date of maintenance. In their articles on the disruption recovery problem, Sarac et al. (2006) and Medard and Sawhney (2007) discuss an effective recovery procedure when the flight or maintenance schedule is disrupted. Bazargan's article on the aircraft boarding problem (2007) analyzes an effective passenger boarding procedure in a parked airplane. The aircraft landing problem (Soomer and Franx 2008) helps the control tower perform effectively within about 30 minutes after the control radar system captures an airplane and swiftly recover the perturbation of the pre-planned schedule before it causes a dangerous situation.

The military air force has more difficult scheduling problems than commercial airlines, such as the management of frequently arriving and departing of airplanes in an air base. The purpose of their scheduling is totally different from the commercial scheduling—*readiness*, in a word. Raffensperger and Schrage (2008) consider a tank scheduling problem for 58 tanks and 600 crew and secure the readiness of the tanks by qualifying crews. Raffensperger and Swords (2003) also focus on the readiness of the electronic warfare aircraft EA-6B Prowler by scheduling four crews (pilots and ECM operators) for flights. They propose a linear programming formulation for flight scheduling to keep the readiness of a Prowler squadron high by managing their qualification, which is acquisitioned when pilots complete training courses but is lost by the qualification's expiration. Some research has explored the scheduling of aircraft squadron, for example, the U.S. Marine (Brown, 1995) and fighter F-14 squadron (Walker, 1992). Comb and Moore (2004) consider the crew scheduling of tanker aircraft by utilizing the Tabu search algorithm and set partitioning technique under the criterion of the minimum cost under some constraints from regulations on crew flight and rest time. Hahn and Newman (2008) make an effective deployment plan to locate Sikorsky HH-60Js of the U.S. Coast Guard and relocate them to the Clearwater air base or other bases by taking account of their missions and maintenance activities.

In Japan's armed forces, the *Self-Defense Forces*, the better scheduling of aircrafts is desired from the viewpoint of the efficient usage of the military budget. The rotary-wing aircraft SH-60J, which belongs to the Japan Maritime Self-Defense Force (JMSDF), plays an important role in anti-submarine warfare (ASW) operations and naval convoys. Other than these military operations, it was effective in some emergency situations: global cooperative activities against terrorism (2001), handling the intrusion of a Chinese submarine into Japanese territorial waters (2004), emergency assistance for the disaster caused by the major earthquake off the cost of Sumatra and Tsunami in the Indian Ocean (2004), and others. Because the success or failure of the helicopter missions mainly depends on the capability of crews, upgrading or maintaining the mission capability of crews is required for the scheduling.

The scheduling of an SH-60J flight is usually done manually in many air wings.

The scheduling staffs spend a great deal of time to create a fair and feasible schedule. We can easily imagine the complexity of their work because they must consider various conditions or constraints on scheduling. Therefore, we start by proposing a mathematical programming method to cope with the complicated situation and ease the workload of the staffs. We could make some conditions, which the staffs implicitly assume, visible through the project. By the mathematical programming method, we can explicitly incorporate complicated conditions in our formulation and clarify the different purpose of elemental scheduling in the entire scheduling by defining its objective function.

SCHEDULING OF SH-60J

Planners usually know the number of available SH-60Js and available simulators, their flight time, and the members to be assigned in advance of scheduling. We deal with a one-week scheduling to assign crews to real flights and simulator training, and specify their seats. First, assume that pre-planned real flights or simulator training courses are given as bars in Figure 1 but are not assigned to any crew. A number written in front of the bar is the specified number of the flight and the simulator training course. A character W, O, T, or N indicates the type of simulator (the individual meaning of these characters is explained later). After our scheduling, we obtain bars with crew names (crews' ID numbers) and their reserved seats as outputs.

In the scheduling of the SH-60J, we consider crew type, training type, and mission type, as we outline next.

Crew Type and Flight

SH-60J has four crews: two pilots, who are in charge of maneuvering the aircraft; and sensormen, who operate equipment and weapons such as sonars and torpedoes. The pilots (main pilot and co-pilot) take front seats and the sensormen take back seats. One team consists of two pilots and one or two sensormen. We assume that we have the list of all members of pilots and sensormen of a relevant squadron in hand.

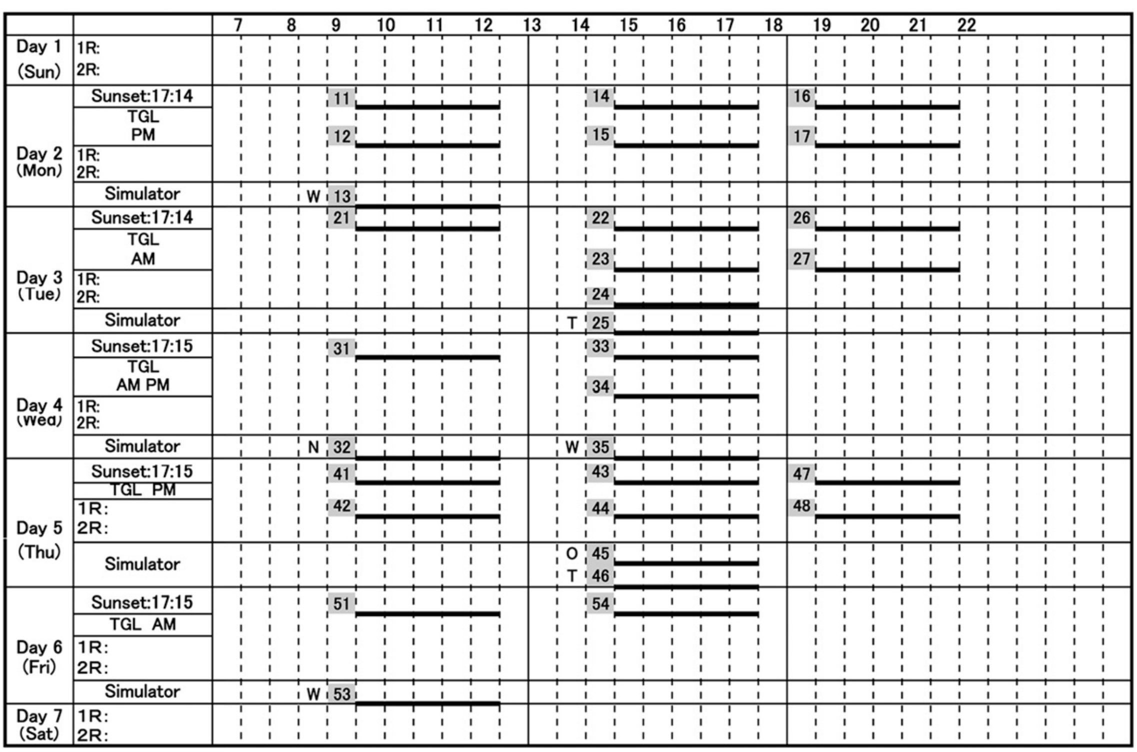

Figure 1. A set of empty flights before scheduling.

In the scheduling, crews are assigned to operational simulators as well as real flights of the SH-60J. The simulator is the necessary hardware for crews to take training in safety and efficiency.

Training Type

Crews have several types of training: real flight by SH-60J and four types of simulators. We represent the real flight using a letter ''F.'' WST (W for short) is the comprehensive training by all crew members; it provides trainees with a realistic environment of the training. OFT (O) is the simulator for the pilot, SOT (T) and SNT (N) are used for the sensorman training. As explained earlier, an SH-60J has four seats but simulators W, O, T and N have many seats to effectively use their functions. Some crew is sometimes assigned to the simulator's operator seat. In an unscheduled flight table such as that in Figure 1, training type is written beside the bar to show which type of simulator is available.

Mission Type

Crews always have a certain mission for their flights. Here we explain three types of the missions.

Qualification and skill training. Qualification (*qual*) is the authorized grade indicating the skill level and knowledge level of crews. The pilot has six quals—1PA, 1PB, 1PC, 2PA, 2PB, and 2PC, from high level to low level—and the sensorman has three quals—SMA, SMB, SMC. The rule prescribes which quals each mission requires for the crews.

To get the qual, the crew has to pass the skill-training course provided with specified syllabus about the training type, training contents, the assignment of seat, the qual required for instructor, and so on (SH-60J Training Standards, 2004). They have six training courses: 1PA, 1PB, 1PC, 2PA, pre-commissioning, and familiarization. The syllabus also specifies the order of training sequence. For example, the crew learns emergency escape in seat #1 at the first class, a basic flight in seat #1 by training type F or W at the second class, a night flight of F on board at the third class, and so on. The training sequence must be perfectly satisfied on scheduling. When we schedule the training course for a crew or trainee, we assign a class of his training course or an element of the syllabus to a bar in the unscheduled flight table and reserve a seat for him. In the similar way to the pilot, the sensorman has four training courses of SMA, SMB, SMC, and familiarization but the constraints prescribed by its syllabus are not so exact as the pilot course.

At the beginning of the relevant week, a commander and his squadron staffs decide which crew takes which training course. They have a database, in which quals and their progress of the training courses of all members are listed. The assignment of pilots to the training courses includes the designation of unscheduled flights to the training courses. As well as trainee, other high-qualified members are assigned as trainers or instructors of the training courses. The scheduling of instructors is different from the scheduling of trainees, however.

Because the qual is the official certification of crew skill and it shows the comprehensive skill level of the squadron for missions, the training course for quals is the most important for each crew and the squadron, and it is the most important target for the scheduling, too.

Emergency ready. For the emergency ready mission, every day one or two crews stay ready for emergent dispatching for emergent accidents, emergent disaster relief operations, or emergent transportation of injured persons. The first crew to be dispatched is referred to as the 1st ready team and the second crew as the 2nd ready team. On scheduling of the emergency ready, we must consider the quals of crews for the emergent mission. The most important criterion for the scheduling is the equality of assigning crews because the ready mission forces crews to stay at the base for long time, almost a whole day. Our scheduler must schedule crews on an equal basis by taking account of past records of all crews on the ready mission.

Maintenance of skill level and assignment of instructor. Skill maintenance training is done not to degrade the quals of the crews or to keep their skill levels. The training types for the maintenance are the same as the skill training: F, W, O, T, and N. The skill maintenance training has lower priority than the skill training and the emergency ready mission. Thus, the skill maintenance training is usually scheduled to the nonoccupied flights after the scheduling of the latter two missions. However, all crew members desire to keep or upgrade their skill levels through maintenance training, so the scheduling for the maintenance training must also be done on the basis of equality or fairness, considering members' past records.

The instructor must have high-level quals to teach trainees in the skill-training course. On the scheduling of assigning instructors, the constraints on the quals are rigid. Course examination is involved in the syllabus of the skill-training course and is done by 1PA instructors with the exam-qual.

SEQUENTIAL SCHEDULING AND OBJECTIVES

In our scheduling, we designate mission type and assign crews with adequate quals to each flight or each bar in an unscheduled flight table like Figure 1. As explained in the previous section, the three mission types have different priorities and purposes. Therefore, we sequentially schedule the flights for each mission using different linear programming formulations. We make the schedule for each course of the skill training of pilots and sensormen first, and then make one for the emergency ready mission while fixing the results of the first scheduling. The schedule for the skill maintenance and the instructor assignment is made last, keeping all results of previous scheduling untouched. We formulate each sequential scheduling using linear programming while describing its objective function and constraints in detail. From here, we focus on the scheduling for pilots and skip the sensormen scheduling because the constraints for both crew types are almost independent of each other and the constraints on the sensorman's schedule are not so tight.

Preliminary: Generation of Records of Crews and Data

From a personal database of the course of skill training he or she progresses as a trainee and how many classes he or she has completed, the squadron commander decides who will enter the skill-training courses and how many classes the trainees take in the courses each week.

After reserving the pre-planned untouchable mission flight in the unscheduled flight table (Figure 1), the staffs in charge of scheduling characterize remaining flights by the following classification: training type (F: Real flight, W: WST, O: OFT) and time zone (AM, PM, N(night)).

Scheduling for Skill Training

Through these six elemental schedulings, we assign all trainees to specific seats of flights in the order of the courses of 1PC, 1PB, 1PA, 2PA, pre-commissioning, and familiarization for pilots. A mixed integer programming problem (MIPP) is generated for the individual scheduling of each training course and solved by commercial software or a solver of mathematical programming. Once the scheduling of a training course is finished, its result or the assignment of the trainees is embedded in the next MIPP as fixed. The objective of the scheduling is to minimize the maximum number of the assigned flights on a day and level the number of skill-training flights over the week. For each MIPP, we set two types of constraints on variables: common conditions for all skill-training courses and special ones for each.

Scheduling for Emergency Ready Mission

After the scheduling for the skill training, we next plan who rides in which seat of which flight for the ready mission using another mixed integer programming formulation. In scheduling, we generate an objective function to flatten workloads over the crew members judging from past records—for example, the number of ready mission flights assigned on holidays and weekdays. As an objective, we take the sum of the cumulative weighted records over the crews with weight 3 for the ready mission on holiday and 2 on weekdays and 1 for the second ready mission. A solution of the MIPP assigns the ready mission flights in such a way that the crews with smaller weighted cumulative record are more likely to be assigned to ready mission flights.

Maintenance of Skill Level and Assignment of Instructor

Without changing the schedule made for the skill training and the emergency ready mission, we designate unscheduled crews as instructors for the skill-training flights, which are already scheduled to trainees, or as the crews of the skill maintenance training. We also use the database of private past records on training type, flight hour, and seat, in such a way that the record type has weight as follows. The personal record is classified in four categories: F night flight in Seat #1~#5 (Category 1), F daytime flight in Seat #1~#5 (Category 2), W flight (Category 3), and O/T/N flight (Category 4). The weight is set to be 4 for Category 1, 3 for Category 2, 2 for Category 3, and 1 for Category 4. We take the sum of weights specified to the categories in their records over the unscheduled crews as the objective function.

Here, we summarize the characteristics of elemental schedulings in our sequential scheduling.

- Among our scheduling, the skill-training scheduling is more important than others and, therefore, must be done first in our sequential scheduling. There are some exceptions, of course. Pre-planned missions and emergency transportations of injured persons have top priority. However, we do not take them as the target for our scheduling.
- For the skill-training schedule, the constraints or conditions must be satisfied. In particular, the order of training classes must be strictly maintained. However, the objective is flexible. We minimize the maximum number of skill-training flights per day and balance the number of flights over the week so that scheduling for remaining flights is easier to do after the skill-training scheduling.
- The emergency ready mission usually ties up the crews for a long time. Therefore, the mission has to be scheduled based on equality or fairness over all crews, and its objective function is generated by taking account of the crews' past records.
- The purpose of the skill maintenance scheduling is to give each crew as many flights as possible such that the crews do not degrade their proficiencies. The scheduling also has to be done on an equitable basis.

As mentioned above, there are some differences among the elemental schedulings and each scheduling has an inherent objective so that we cannot unify those scheduling into one. The squadron usually has a kind of slack on human resource in realistic cases and our sequential scheduling procedure is always feasible even under some perturbation. This is why we adopt the sequential scheduling procedure.

CATEGORY OF CONSTRAINTS

We categorize the constraints of the sequential scheduling into four types.

Constraints on Seat

Especially in the skill-training course, the trainees or instructors are required to have specific seats, which are written in the syllabus. For example, Seat #1 on an F type of flight has to be seated by a trainee with 2PB or higher level of qual.

Constraints on Combination of Crews

There are prohibitions on some combinations of crew members on board from the viewpoint of qual, rank, and others. For example, classmates in the same alumni association are prohibited from being on the same flight and the pilot in the first seat must have higher rank than the pilot in the second seat in the emergency ready flight.

Constraints on the Training Pattern

In the rules of the skill-training courses, there are some constraints on the training type, the order of classes, quals required for the trainees and instructors, and others. They are usually documented in the syllabus of each course.

Constraints on Combination of Flights

Some combinations of flights could be risky from the view of pilot workload. For example, the pilots assigned to the emergency ready mission must not take other flights on the same day and are recommended not to be on a flight the day after or the day before. The pilot must not take real flights immediately after the simulator training because of possible occurrence of the fake impression on the five senses.

Either type of constraint must be considered in each elemental scheduling to some extent. We describe how each type of constraints is taken into account for each scheduling in Table 1, which indirectly shows the characteristics of each scheduling.

FORMULATION BY A MIXED INTEGER PROGRAMMING PROBLEM

Here, we describe each sequential scheduling as a 0–1 mixed integer programming problem. Because we cannot describe all constraints due to the page limit, we show some of them. We need a technique to represent constraints by some expressions and manipulate the solution of the problem in our desirable direction using the mathematical programming formulation. Especially, the constraints on the skill-training course are expressed such that the sequence of scheduled flights complies with the syllabus on a time axis. The generation of the constraints will be described later. We focus on the scheduling not for the sensorman but for the pilot because the scheduling for both pilot and sensormen usually can be done independently of each other and the sensorman's schedule is much simpler than that of the pilot.

Please refer to the ''Sequential Scheduling and Objectives'' section, where we explained the purpose of each scheduling and the meaning of its objective function. First, let us describe a summary of the notation.

Notation

$\boldsymbol{D}$: $\{1, 2, \ldots, 7\}$: a set of days for scheduling (one week); 6 is Saturday and 7 is Sunday
$\boldsymbol{P}$: a set of pilots
$\boldsymbol{P}_{Ns}$: a set of crews, who are not trainees, with qual $s \in \{1PA, 1PB, 1PC, 2PA, 2PB, 2PC\}$
$\boldsymbol{P}_s$: a set of trainees in the skill-training course for qual $s \in \{1PA, 1PB, 1PC, 2PA, Sy, PKa\}$, where Sy and PKa are the courses of the precommissioning training and the familiarization training, respectively
r_p: rank of pilot $p \in \boldsymbol{P}$
a_p: graduation year in alumni for pilot p
$\boldsymbol{A}_k^P$: a set of pilots with graduation year k in alumni
$\boldsymbol{F}$: a set of flights. The flights are numbered in the precedence order along a time axis.
$\boldsymbol{F}_N$: a set of night flights
$\boldsymbol{F}^l$: a set of flights with training type $l \in \{F, W, O\}$
$\boldsymbol{F}_k^l$: a set of flights with training type l at the kth day
$\boldsymbol{F}_k^R$: a set of ready mission flights at the kth day

Table 1. Types of constraints and their rigidness for each scheduling.

Scheduling types	Type of constraints			
	Seat	Companion	Training pattern	Flight comb.
1PA Training	B	B	A	B
1PB Training	B	B	A	B
1PC Training	C	B	A	B
2PA Training	C	B	A	C
Pre-commissioning	C	C	A	C
Familiarization	C	C	A	C
SMA Training	B	B	A	B
SMB Training	C	C	A	C
SMC Training	C	C	A	C
Familiarization	C	C	A	C
Ready	B	A	–	A
Skill Maint.	C	C	–	C

A: Very severe, B: Severe, C: So-so, –: None

$\boldsymbol{F}^{t}_{k,l}$: a set of flights with training type l in the morning, in the afternoon, or at night $t \in \{AM, PM, N\}$ at the kth day
$\boldsymbol{A}^{P}_{a}$: a set of pilots with the same graduation year a in alumni
$\boldsymbol{C}_P$: a set of seats for pilot use
$\boldsymbol{C}^{l}_{P}$: a set of seats that a pilot takes for training type $l \in \{F, W, O\}$
$\boldsymbol{C}^{l+}_{P}$: a set of auxiliary seats which a pilot takes for training type $l \in \{F, W, O\}$

Variables and Common Conditions

We use a 0–1 variables x_{pfc}, which is 1 if pilot $p \in \boldsymbol{P}$ takes seat $c \in \boldsymbol{C}_P$ in flight $f \in \boldsymbol{F}$ and 0 otherwise. There are 14 types of conditions as common constraint in our scheduling. We show some of them.

- Main seats must be occupied by a crew in the real flight or the simulator training.

$$\sum_{p\in \boldsymbol{P}} x_{pfc} = 1, \quad c \in \boldsymbol{C}^{l}_{P}, \quad f \in \boldsymbol{F}$$

- A pilot must not take training in the real flight at the same day when he/she takes some simulator training.

$$\sum_{l\in\{W,O\}} \sum_{c\in C^{l}_{P}} \sum_{f\in \boldsymbol{F}^{AM}_{k,l}} x_{pfc} + \sum_{c\in C^{F}_{P}} \sum_{f\in \boldsymbol{F}^{PM}_{k,F}} x_{pfc} \le 1, \quad p \in \boldsymbol{P}, \quad k \in \boldsymbol{D}$$

$$\sum_{l\in\{W,O\}} \sum_{c\in C^{l}_{P}} \sum_{f\in \boldsymbol{F}^{AM}_{k,l}} x_{pfc} + \sum_{c\in C^{F}_{P}} \sum_{f\in \boldsymbol{F}^{N}_{k,F}} x_{pfc} \le 1, \quad p \in \boldsymbol{P}, \quad k \in \boldsymbol{D}$$

$$\sum_{l\in\{W,O\}} \sum_{c\in C^{l}_{P}} \sum_{f\in \boldsymbol{F}^{PM}_{k,l}} x_{pfc} + \sum_{c\in C^{F}_{P}} \sum_{f\in \boldsymbol{F}^{N}_{k,F}} x_{pfc} \le 1, \quad p \in \boldsymbol{P}, \quad k \in \boldsymbol{D}$$

Scheduling for Skill Training

The most important function of the scheduling is to assign flights to the classes of the skill-training courses in accordance with the syllabus. We will explain an important scheduling technique to satisfy the precedence of the syllabus, later. For the skill training, we set an objective function and constraints, as follows. We can categorize the constraints in 18 types, some of which are shown below.

Formulation for skill-training course $s \in \{Ka, Sy, 2PA, 1PC, 1PB, 1PA\}$

$$\min_{x} \eta$$

$$\sum_{p\in \boldsymbol{P}_s} \sum_{l\in\{F,W,O\}} \sum_{c\in \boldsymbol{C}^{l}_{P}} \sum_{f\in \boldsymbol{F}^{l}_{k}} x_{pfc} \le \eta, \quad k \in \boldsymbol{D}$$

- (Familiarization) In simulator WST, a trainee takes Seat 1. An instructor in Seat 2 must have qual *1PA* and a crew with *1PC* or *1PB*, not trainee, takes a ‘‘console’’ seat as an operator of equipments.

$$2\sum_{p\in \boldsymbol{P}_{Ka}} x_{pf1} \le \sum_{p\in \boldsymbol{P}_{N1PA}} x_{pf2} + \sum_{p\in \boldsymbol{P}_{N1PC}\cup p\in \boldsymbol{P}_{N1PB}} x_{pf\,con}, \quad f \in \boldsymbol{F}^{W} \tag{1}$$

- (2PA course) An instructor in Seat 2 must have *1PA* or higher qual for the skill training.

$$2\sum_{p\in \boldsymbol{P}_{2PA}} x_{pf1} \le \sum_{p\in \boldsymbol{P}_{N1PA}} x_{pf2}, \quad f \in \boldsymbol{F}$$

Scheduling for Emergency Ready Mission

For the scheduling of the emergency ready mission, we summarize notation, an objective, and the constraints of the formulation. Although there are 12 types of constraints, we use two types as examples.

Notation

$\boldsymbol{F}^{lR}_{k}$: a set of flights for the first or the second ($l = 1$ or 2) ready mission at the kth day
$\boldsymbol{F}^{R}_{k}$: a set of flights for ready mission at the kth day. $\boldsymbol{F}^{R}_{k} = \cup_{l\in\{1,2\}} \boldsymbol{F}^{lR}_{k}$
$\boldsymbol{F}^{lR}$: a set of flight numbers for the lth ready mission. $\boldsymbol{F}^{lR} = \cup_{k\in D} \boldsymbol{F}^{lR}_{k}$
$\boldsymbol{C}^{R}_{P} = \{1, 2\}$: a set of seats for pilots for ready mission
$\boldsymbol{P}_V$: a set of veteran pilots who take the right seat
$\boldsymbol{P}^{R}_{2}$: a set of pilots, who were assigned to ready mission twice last week

rt_p^H: the number of the assignments of Pilot p to ready mission on holiday in the past (times per past two months)
rt_p^l: the number of the assignments of Pilot p to the lth ready mission in the past (times per past two months)
Rw^H: weight for ready mission on holiday
Rw^l: weights for the lth ready mission, $l = 1, 2$. (Usually, $Rw^H > Rw^1 > Rw^2 = 1$.)

Formulation for emergency ready mission

$$\min_x \sum_{p \in \boldsymbol{P}} \sum_{c \in C_p^R} \left(\sum_{f \in \boldsymbol{F}_6^R \cup \boldsymbol{F}_7^R} Rw^H \cdot x_{pfc} \cdot rt_p^H + \sum_{l \in \{1,2\}} \sum_{f \in \boldsymbol{F}^{lR}} Rw^l \cdot x_{pfc} \cdot rt_p^l \right) \tag{3}$$

- The rank and the graduation year in alumni of a pilot in the first seat are higher than those of a pilot in the second seat.

$$\sum_{p \in \boldsymbol{P}} x_{pf1} \cdot r_p \geq \sum_{p \in \boldsymbol{P}} x_{pf2} \cdot r_p, \quad f \in \boldsymbol{F}_k^R, \quad k \in \boldsymbol{D}$$

$$\sum_{p \in \boldsymbol{P}} x_{pf1} \cdot a_p + 1 \leq \sum_{p \in \boldsymbol{P}} x_{pf2} \cdot a_p, \quad f \in \boldsymbol{F}_k^R, \quad k \in \boldsymbol{D}$$

- The crews assigned to the first ready mission should not take any other flight at the same day.

$$\sum_{f \in \boldsymbol{F}_k^{1R}} \sum_{c \in \boldsymbol{C}_P^R} x_{pfc} + \sum_{l \in \{F,W,O\}} \sum_{f \in F_k^l} \sum_{c \in \boldsymbol{C}_P^l \cup \boldsymbol{C}_P^{l+}} x_{pfc} \leq 1, \quad p \in \boldsymbol{P}, \quad k \in \boldsymbol{D}$$

Scheduling for the Skill Maintenance Flight and Assignment of Instructor

Personal data on flights is classified into four categories, as mentioned in the ''Sequential Scheduling and Objectives'' section, and each category has an inherent weight. The objective function of the scheduling is made from the sum of weights over all pilots according to the category like Equation 3, but the expression is too long to describe here.

Please note that the schedule for trainees of the skill-training course, which has been already done, is now fixed—that is, x_{pcf} is fixed for every trainee p. However, some instructors have been temporarily assigned in the skill-training scheduling for the feasibility check of the training course. Those are cancelled here and the assignment of instructor is renewed for the scheduled flight of the skill training. Some crews might also be scheduled to some skill-training flights as assistant crew or auxiliary.

In the assignment of instructors and auxiliaries, we take account of the same constraints as in the scheduling for the skill training, as shown in the following example. The constraints for the skill maintenance flight are not so special that some crews are assigned to the maintenance flights under common constraints.

- In the OFT training class of 1PB, an instructor must have 1PA or higher qual for the second seat and 2PA or 1PC qual for the auxiliary (''a'') seat, while the first seat is reserved for a trainee.

$$2 \sum_{p \in \boldsymbol{P}_{1PB}} x_{pf1} \leq \sum_{p \in \boldsymbol{P}_{N1PA}} x_{pf2} + \sum_{p \in \boldsymbol{P}_{N2PA} \cup \boldsymbol{P}_{N1PC}} x_{pfa}, \ f \in \boldsymbol{F}^O$$

Scheduling to Comply with the Precedence of Classes in the Training Course

This scheduling is a part of the skill-training scheduling. It focuses on the compliance with the precedence of classes in a training course so that we need a specified technique of scheduling. Here we describe its special formulation by mathematical programming. The followings are a summary of notation and the definition of variables.

Notation

- $\boldsymbol{P}_S = \boldsymbol{P}_{Ka} \cup \boldsymbol{P}_{Sy} \cup \boldsymbol{P}_{2PA} \cup \boldsymbol{P}_{1PA} \cup \boldsymbol{P}_{1PB} \cup \boldsymbol{P}_{1PA}$: a set of pilot trainees for all skill-training courses
- $\boldsymbol{F}_P^{ALL} = \boldsymbol{F}^F \cup \boldsymbol{F}^W \cup \boldsymbol{F}^O$: a set of available flights for pilots

- L_p: the number of classes in the training course which Pilot p is going to take
- SY_p^l: a vector with the position numbers of training type l allocated in the precedence of a one-week training course for Pilot p
- L_p^l: the number of l-type training classes in a one-week training course for Pilot p

To better understand the last two notations, we take an example of a one-week training course as follows. A trainee is supposed to take a class on a real flight (type 'F') first, secondly a simulator exercise by OFT (type O), thirdly a real flight again (type F), and lastly a WST (type W). In this case, parameters are set to be $SY_p^F = \{1, 3\}$, $SY_p^W = \{4\}$, $SY_p^O = \{2\}$, $L_p^F = 2$, $L_p^W = 1$ and $L_p^O = 1$.

We introduce a new variable z_{pfcd}, which is 1 if Pilot p takes Seat c on Flight f in the dth class of the training course and 0 otherwise. We can understand the precedence prescribed in a skill-training course by parameters SY_p^l and L_p^l. We manage to construct the constraints for the compliance of the precedence. The following condition assures the consistency between 0–1 variables z defined above and x defined in the ''Variables and Common Constraints'' section.

$$x_{pfc} = \sum_{d=1}^{L_p} z_{pfcd}, \quad p \in \boldsymbol{P}_S, \quad f \in \boldsymbol{F}, \quad c \in \boldsymbol{C}_P \tag{4}$$

A trainee takes only one flight in the dth class. Therefore, we have

$$\sum_{f \in \boldsymbol{F}} \sum_{c \in \boldsymbol{C}_P} z_{pfcd} = 1, \quad d = 1, \ldots, L_p, \quad p \in \boldsymbol{P}_S \tag{5}$$

In the dth class, $d \in SY_p^l$, only a type-l flight is taken. The uniqueness of the flight for d and l is represented by

$$\sum_{f \in \boldsymbol{F}} \sum_{c \in \boldsymbol{C}_P} z_{pfcd} = 1, \; d \in SY_p^l, \quad l \in \{F, W, O\}, \quad p \in \boldsymbol{P}_S \tag{6}$$

The most important condition is that d – 1 classes must have been completed before the dth class. The precedence of classes is kept by the following constraint:

$$\begin{aligned}(L_p + d)\left(\sum_{c \in \boldsymbol{C}_P} z_{pfcd} - 1\right) &\le \sum_{d'=1}^{L_p} \sum_{f' \le f, f' \in \boldsymbol{F}_P} \sum_{c \in \boldsymbol{C}_P} z_{pf'cd'} - d \\ &+ L_p\left(\sum_{f' \ge f, f' \in \boldsymbol{F}^l} \sum_{c \in \boldsymbol{C}_P} z_{pf'cd} - 1\right) \le 0, \\ f \in \boldsymbol{F}^l, \quad d \in SY_p^l, &\quad l \in \{F, W, O\}, \quad p \in \boldsymbol{P}_S\end{aligned} \tag{7}$$

This condition works in the following manner. If $\sum_{c \in \boldsymbol{C}_P} z_{pfcd} - 1 = 0$ by taking flight f in the dth class, the left-hand side of Equation 7 becomes 0, which makes the middle expression zero. That means that there must be d classes scheduled somewhere including the current class. If the current class d is not scheduled, namely $\sum_{c \in \boldsymbol{C}_P} z_{pfcd} = 0$, the condition above does not work as any constraint in practice.

We can apply the similar formulation to other special cases.

- Permission for multiple training types: If we denote a set of classes, at which both training types A or B are permitted, by SY_p^{AB}, we would modify constraints (6) and (7) as follows:

$$\sum_{f \in \boldsymbol{F}_p^A \cup \boldsymbol{F}_p^B} \sum_{c \in \boldsymbol{C}_p} z_{pfcd} = 1, \quad d \in SY_p^{AB}, \quad p \in \boldsymbol{P}_S \tag{8}$$

$$\begin{aligned}(L_p + d)\left(\sum_{c \in \boldsymbol{C}_P} z_{pfcd} - 1\right) &\le \sum_{d'=1}^{L_p} \sum_{f' \le f, f' \in \boldsymbol{F}_P} \sum_{c \in \boldsymbol{C}_P} z_{pf'cd'} - d \\ &+ L_p\left(\sum_{f' \ge f, f' \in \boldsymbol{F}^A \cup \boldsymbol{F}^B} \sum_{c \in \boldsymbol{C}_P} z_{pf'cd} - 1\right) \le 0, \\ f \in \boldsymbol{F}^A \cup \boldsymbol{F}^B, &\quad d \in SY_p^{AB}, \quad p \in \boldsymbol{P}_S\end{aligned} \tag{9}$$

- Designation of training type and time zone to the class: If training type A and time zone T (for example, AM, PM, or night) are designated to a class of the training course and we denote a set of the classes by SY_p^{AT}, we would modify constraint (6) by

$$\sum_{k\in \boldsymbol{D}} \sum_{f\in \boldsymbol{F}_{k,A}^{T}} \sum_{c\in \boldsymbol{C}_P} z_{pfcd} = 1, \quad d \in SY_p^{AT}, \quad p \in \boldsymbol{P}_S$$

NUMERICAL EXAMPLES

Now we take two cases of flight scheduling in a real squadron, which has 81 crew members in total. Out of 81 people, we consider the scheduling of 62 crew members of 31 pilots and 31 sensormen as the target of the scheduling. Out of 31 pilot and 31 sensormen, 17 pilots and 7 sensormen are trainees for the skill-training course. We assign ID number 1 through 31 to individual pilots. Each sensorman has an ID number larger than 50. Figure 1 is a typical set of blank flights before scheduling. Case 1 of 30 bars or 30 blank flights is shown in Figure 1. We assign 62 crew members to 30 blank flights using our scheduling method. For the scheduling, we use a personal computer FUJITUU FMV mounted with Pentium 4 CPU of 60 GHz and software NUOPT Version 6 as the solver of mathematical programming. We use data or records of crew members from the existing database of qual, training course, graduation year in alumni, rank, categorized flight hour, and so on.

Figure 2 shows the result of the scheduling. The format of Figures 1 or 2 is approximately the same as used in the squadron. The left column indicates the date and the day of the week. The second column shows the time of sunset, the time period of the touch-and-go landing training, a blank space to note the crews of the first and second ready mission and the word ''Simulator,'' which indicates the row for the simulator training. Each flight has an identification number (flight number) and each simulator training has an additional letter W, O, T, or N, representing the type of simulator. On Saturday and Sunday, there is no flight except the ready mission by two teams.

Our scheduling system assigns ID numbers of pilot and sensorman to the blank flight and the ready mission. Our system sequentially schedules the skill-training course of 1PC, 1PB,

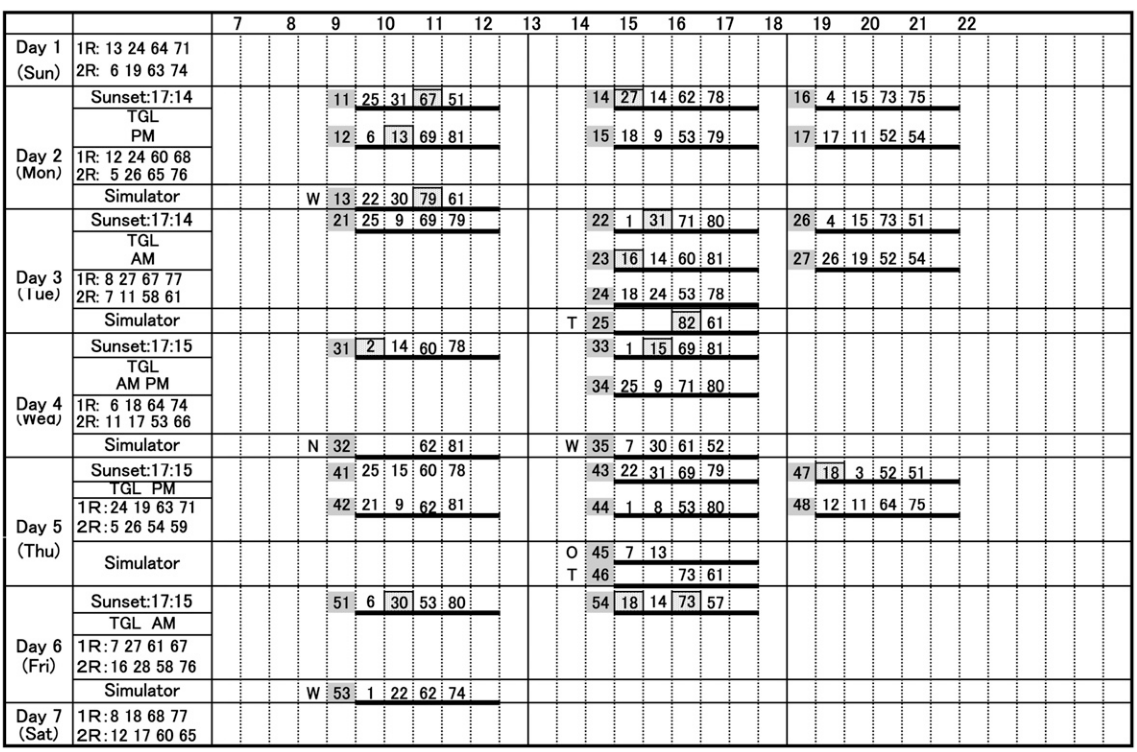

Figure 2. Schedule for 62 crew members and 30 flights.

1PA, 2PA, pre-commissioning, and familiarization step by step. Following the elemental scheduling, the system schedules all sensorman trainees in SMA, SMB, SMC, and familiarization courses in one step. After that, the daily ready mission flights of two teams are scheduled and, in the last scheduling, the unscheduled crews are assigned to the flight of the skill-maintenance training and the instructor in the skill-training flight.

In Figure 2, the space for the first and the second ready mission or the space above the bar of flight is filled with four crew numbers in the order of the first seat (main pilot front seat), the second seat (co-pilot front seat), the third seat (the 1st sensorman back seat), and the fourth seat (the 2nd sensorman back seat). Four crews are assigned to a WST (W) simulator but just two pilots to an OFT (O) and two sensormen to a SOT (T) or a SNT (N). Exceptional assignment is sometimes made to an operator seat of the simulator and to an additional back seat of real flight for the training support staff.

Figure 1 is an ordinary setting of flights by the squadron with about 80 members. We generate another trial case of 45 blank flights (Case 2), which has 1.5 times the number of flights of the first case, to check the efficiency of the proposed scheduling method and illustrate the result in Figure 3. We use the same data about 62 crew members as in Case 1, but there are two differences between the parameter settings of Cases 1 and 2. One is the number of blank flights and the other is the number of flights to be used for the skill training. We assign nine flights and five flights for the skill training of pilot and sensorman, respectively, in Case 1, and 15 flights and six flights in Case 2. We explain the detail of the setting later. In Table 2, we show the number of variables (var. #), the number of constraints (const. #), and computational time (time(sec)) generated or consumed for the integer programming formulation of six skill-training courses of pilot (1PC, 1PB, 1PA, 2PA, pre-commissioning (Pre.), familiarization (Fami.)),

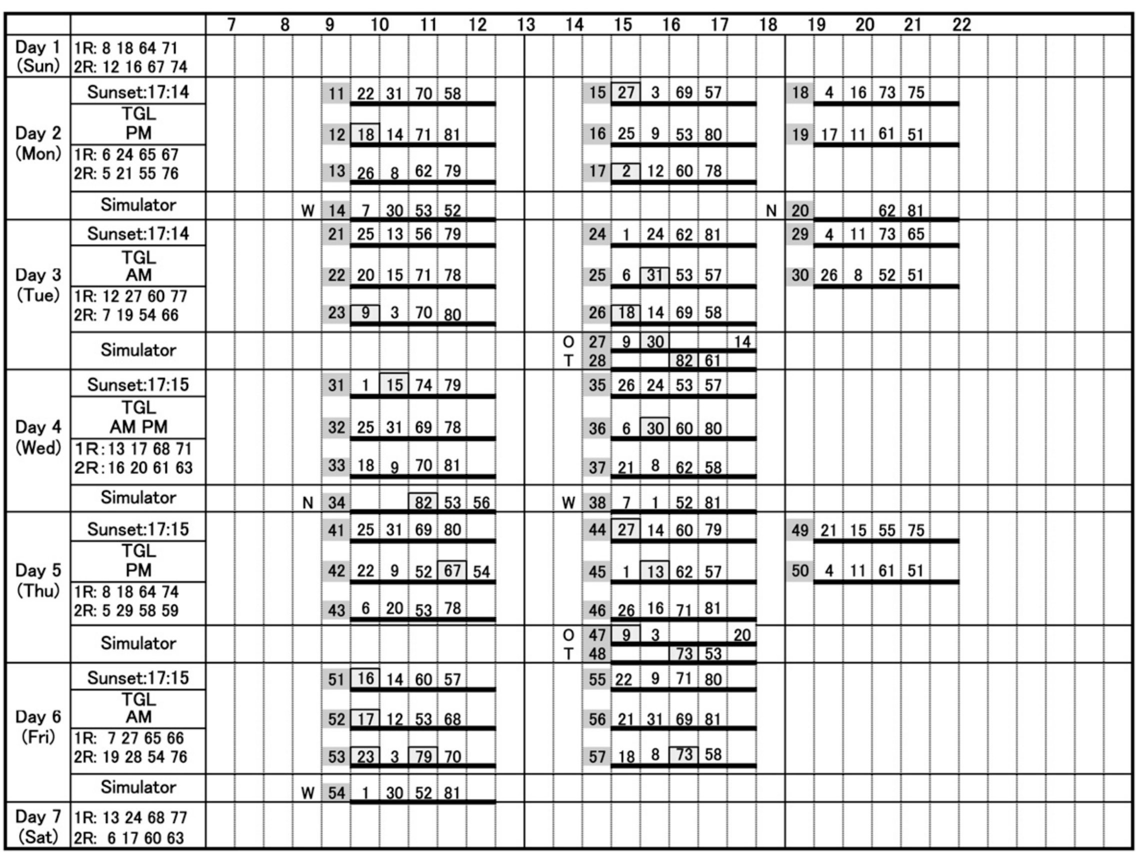

Figure 3. Schedule for 62 crew members and 45 flights.

Table 2. Size of problem and computational time.

	1st Case			2nd Case		
	Var. #	Const. #	Time(sec)	Var. #	Const. #	Time(sec)
1PC	5593	3904	1.5	8622	5188	73.7
1PB	4734	3692	2.7	7617	4848	52.5
1PA	4859	3690	2.4	7422	4780	15.9
2PA	4667	3558	3.7	7510	4708	25.0
Pre.	4725	3466	1.7	7403	4444	49.7
Fami.	4600	3443	1.6	7013	4396	18.7
SM	3960	2905	3.1	6294	4058	13.2
Ready	6542	5851	353.6	8836	7785	477.8
Maint.	6250	5503	0.4	8936	6942	0.8
Total			370.6			727.2

four skill-training courses of sensorman (SMA, SMB, SMC, Fami.), abbreviated by SM, emergency ready mission (Ready), and skill maintenance training & assignment of instructors (Maint.).

Because the number of variables and constraints is large and the combination of flights and companions is complicated in the ready mission scheduling, its feasible region of solution seems to be small. That is why the computational time for ''Ready'' is large. Before the scheduling of ''Maint.,'' almost all crews have been already scheduled and a solution of ''Maint.'' requires a tiny time for its computation. Case 2, which is about 1.5 times as large as Case 1 in terms of the number of blank flights and the number of flights provided for the skill training, requires about twice the computational time of Case 1. We cannot say that the proposed algorithm works so efficiently for larger size of problem, but 6~12 minutes would be no problem for the computation of the one-week scheduling. From the results in the ordinary size of Case 1, our scheduling method is estimated to reduce the time of the manual work by planning specialists to about 1/30.

Next we must check the detail of the result of Case 2 in Figure 3. In this case, trainees in the skill-training course for pilot are 7, 13, 15, and 24 (4 pilots) in the 1PA course; 9, 11, 16, and 25 (4) in 1PB; 17 and 18 (2) in 1PC; 23, 27, and 28 (3) in 2PA; 30 and 31 (2) in pre-commissioning (Pre.); 2 and 10 (2) in familiarization (Fami.). Sensorman trainees are 67 (1 sensorman) in SMA course; 73 and 75 (2) in SMB; 79, 80, and 81 (3) in SMC; 82 (1) in Fami. Some of them join their courses in this week but pilots 7, 10, 11, 24, 25, 28 and sensormen 75 and 80 are supposed to be on the flight just for the skill maintenance training. Let us look at the assignment of other trainees in Figure 3. Pilot 18 joins two 1PC training classes on flight No. 12 and 26. The syllabus of the second class requires the training by real flight (F) or WST simulator and the answer of the scheduling is the real flight of No. 26. The trainee happens to be instructed on the two flights by the same instructor 14, who has 1PA qual to the database. Trainee 17 is supposed to join one class with examination in the same course as 18 and is assigned to F 52, where pilot 12 with 1PA qual and exam-qual has the second seat in charge of the class as an instructor.

The syllabus of pre-commissioning training course requires trainee 30 to take a class by OFT simulator and a class by WST simulator or F flight. He has the assignment of flight No. 27 and 36. On the first flight by OFT simulator, which 1PA-qualified pilot 14 operates, the trainee is instructed by pilot 9 with 1PC qual in Seat #1. Instructor 9 is also a trainee in the 1PB training course and is arranged to take two classes in Seat #1 on flights 23 and 47 with 1PA-qualified instructor 3 as the result of the scheduling. The syllabus of the skill-training course for pilot prescribes the seat of trainee and trainer, the qualification of trainer and others as well as the training contents of its individual class.

Trainees of sensorman are assigned to some classes of his course in the similar way to the pilot course. But, in the simulator training, they use SOT (T) and SNT (N) other than pilot simulator OFT (O). Almost the flights assigned to sensorman trainees are different from the flights of pilot trainees in the scheduled plan. Therefore, if a sensorman trainee takes classes on some flights, pilot crews are on board of the flight for their skill maintenance. Only exception is flight No. 53, on which pilot trainee 23 takes a class of 2PA course and sensorman trainee 79 has the training of SMC course at the same time. By the scheduling for the skill training, 20 flights of No. 12, 15, 17, 23, 25, 26, 27, 28, 31, 34, 36, 42, 44, 45, 47, 48, 51, 52, 53, and 57 are used for the skill training and other 25 flights are scheduled to the skill maintenance.

Two ready teams are decided every day, including weekends, based on the past record of individual crew. As Table 2 shows, the scheduler consumes more than 65 percent of the total computation time for scheduling the ready team because of the reason mentioned earlier. The result for the ready mission is listed in the second column of Figure 3. By looking into the detail of the assignment, crews with large number of past assignment are not listed in the teams of the ready mission, according to the database. This fact tells that the objective function of Equation (3) would work well on the equality basis for the scheduling.

When we explain the scheduling of the skill training above, we mention the assignment of instructors or exam-qualified instructors for the training classes. In our sequential scheduling procedure, the instructor is assigned by the last elemental scheduling as well as the flight assignment to the skill maintenance. In the examples shown here, the scheduler takes account of not only the constraints and data mentioned in the ''Category of Constraints'' section, but also information about officers on duty of the watch each day and the absence of some crews going out of the squadron for meeting or business.

CONCLUSION

We have shown by the computational examples that our scheduling method by mathematical programming meets practical requirements in terms of computation time. It is particularly useful because it can deal with a variety of conditions or constraints with accuracy. However, the scheduling is still a trial and has not yet been introduced in any squadron. A more advanced and efficient scheduling system would require the connection with a database of crews and the pretreatment of filtering consistency between parameters, through which many constraints can be deleted in the mathematical formulation to simplify the formulation. Our proposition is a prototype for squadron experimentation leading to a practical scheduling system for SH-60J.

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