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Optimized Air Force Flight Scheduling Considering Pilot's Mission Efficiency

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Human and material resource planning is one representative example of Operations Research. Resource planning is important not only in civilian settings but also in military ones. In the Air Force, flight scheduling is one of the primary issues that must be addressed by the personnel who are connected to flight missions. However, although the topic is of great importance, relatively few studies have attempted to resolve the problem on a scientific basis. Each flight squadron has its own scheduling officers who manually draw up the flight schedules each day. While mistakes may not occur while drafting schedules, officers may experience difficulties in systematically adjusting to them. To increase efficiency in this context, this study proposes a mathematical model based on a binary variable. This model automatically drafts flight schedules considering pilot's mission efficiency. Furthermore, it also recommends that schedules be drawn up monthly and updated weekly, rather than being drafted from scratch each day. This will enable easier control when taking the various relevant factors into account. The model incorporates several parameters, such as matching of the main pilots and co-pilots, turn around time, availability of pilots and aircraft, monthly requirements of each flight mission, and maximum/minimum number of sorties that would be flown per week. The optimal solution to this model demonstrated an average improvement of nearly 47% compared with other feasible solutions.

Keywords : Flight Schedule, Efficiency, Assignment

1. Introduction

Operations Research (OR), which was first developed to assist in the execution of military operations during World War Ⅱ, has since been applied to many areas in society, such as service, manufacturing, and communications sectors. As demonstrated by Kasirzadeh et al. [4] and Habibi et al. [2], examples of OR in the service and manufacturing sectors include human and material resource planning. In military applications, resource planning is also of significant importance. In the Air Force, flight scheduling is one of the key focal points for pilots, mechanics, and any other person connected to flight mission support. However, despite the importance of flight scheduling, relatively few efforts have been made to scientifically resolve the issues surrounding it.

Each flight squadron has scheduling officers who are also pilots. Currently, these personnel manually make their squadron's flight schedules every day considering the pilots' missions, achieved qualifications, air zones shared with others, etc. When unexpected circumstances arise, such as aircraft

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deficiencies, weather, and urgent missions, they must immediately revise the schedules manually. Furthermore, scheduling officers must remain in their offices from the beginning to the end of each day's flight schedules; often, pilots also have night duties. Because of this, scheduling officers have insufficient downtime, which can lead to human error. While they may not make mistakes in their duties, it will be difficult for them to systematically keep track of each pilot's condition, experience, and number of flown flights. An unsuitable schedule can also correlate with pilots' fatigue levels, both physical and mental, which, in turn, can further affect their performance [7].

In real life, a schedule is devised with a restricted number of pilots and aircraft. This paper proposes a mathematical model that is capable of automatically producing flight schedules and efficiently considering any constraints related to their creation. Moreover, this study recommends that schedules be drawn up on a monthly basis and updated weekly, rather than each day. This will enable easier control when considering the many relevant factors that come into play. Using this approach to fulfill scheduling guidelines can also help prevent any essential aspects from being overlooked. Moreover, this study could also contribute to human resource management by reducing the workloads of both the pilots and schedulers.

2. Literature Review

Numerous studies have investigated the scheduling practices of commercial airlines [12]. However, few have investigated such scheduling practices in the Air Force context, either domestically or internationally. This may be due to the confidential nature of the military, which makes it difficult to obtain data. The military, which mainly focuses on national security, has different objectives and working environments from commercial airlines, whose main aim is to maximize profits. Commercial airlines have frequent layovers to enable an effective transport of people and commodities. Typically, commercial airlines transport hundreds of people, and their flights span multiple hours. Furthermore, they adjust the number of flights they offer according to their customers' needs. Contrarily, the transport of people and commodities is not the only goal of the military. During peacetime, its main goal is air defense. Military aircraft are usually operated by less than 10 people in total and fly for short periods of time. The military adjusts the number of flights conducted based on national security grounds, not economic ones. Therefore, the circumstances under which commercial airlines are scheduled cannot be directly applied in a study of this nature.

Raffensperger and Swords [8] constructed models for the US Navy's Prowler training schedule. The Prowler is an aircraft that incorporates electronic surveillance and countermeasures. One pilot and three officers fly in it together and train for a total of 45 different qualifications to maintain mission proficiency. These qualifications expire over time, and if officers do not renew them, they cannot partake in missions. Two integer programming models that improve the readiness of officers by approximately 10%, through the prompt renewal of their qualifications, have been proposed.

Vestli et al. [11] presented a weekly training schedule for Norway's combat squadron, which was produced by column generation. They proposed three different methods for generating flight schedules, which were created by solving the master problem, applying Heuristic, and Column Generation. They demonstrated that the master problem and the heuristic's performance worsened when the size of the problem increased. However, with respect to column generation, they were able to determine a solution for a large problem in a short amount of time, though not an optimized one.

Lee and Seo [5] proposed a weekly flight scheduling model for a South Korean Air Force F-16 combat squadron. They considered various factors, such as pilot information, performance, duty eligibility, yearly flight requirements, elapsed time between missions, weather, and safety. Eligibility, yearly flight requirements, and elapsed time between missions were considered as objective functions, whereas pilot information, weather, and safety considerations were considered as constraints. Lee and Seo updated the weekly schedules based on the daily ones.

Choi [1] presented a flight schedule for a two-seater fighter squadron. The study incorporated minimum turn around times, pilot downtime, and the availability of pilots who could fly simultaneously to create a mathematical model. Yearly flight requirement, elapsed time, duty eligibility, and qualifications were taken as objective functions, and weight was given to the yearly requirements and elapsed time to apply flexibility to the planning process.

Commercial airlines also focus on improving the efficiency of their flight schedules. Schaefer et al. [10] found that numerous previous studies that investigated airline crew scheduling did not include any assumptions that disruptions can occur. Thus, they estimated the probability distributions for disruptions caused by delays occurring during flights or at airports using real-world data. They simulated their model and observed that schedules that included the possibility of disruptions demonstrated better performance in operation than those that did not. Scheduling can also be applied in other fields. Jung and Kim [3] investigated the communication scheduling optimization problem of satellites and ground stations, whereas Lee et al. [6] employed simulations for the emergency medical center.

This study was based on real-world data obtained from a Korean search and rescue flight squadron. However, some of the data was reduced or enlarged, such as the number of pilots and aircraft, types of missions flown, and total number of missions, so as to avoid violation of military confidentiality. These data modifications did not influence the overall results of this study. During the literature review, we found that several studies did not consider the number of available aircraft. However, in the real world, the availability of aircraft is a critical factor that must not be disregarded. Therefore, the presented study implemented several constraints relating to this. Our objective function was to maximize the total efficiency of mission completion by pilots. Efficiency in this context is defined in Section 3.1. Finally, in our model, the frequency of flight scheduling was changed to a monthly basis and updated weekly, which is contrary to the current situation, in which schedules are drawn up manually by scheduling officers each day.

3. Mathematical Model

3.1 Definition of Problem

Air Force flight schedules are classified on a monthly, weekly, and daily basis. Monthly schedules include seasonal factors, the availability of resources, and yearly pilot requirements. Weekly schedules consider a pilot's emotional or mental readiness based on the monthly schedule. Daily schedules comprise a detailed plan indicating the flight mission and night duty based on the weekly schedule [9].

Every mission cited in this study was conducted with one main pilot and one co-pilot. It is assumed that there were 10 main pilots, 7 co-pilots, and 5 aircraft in the squadron. The pilots conducted six different types of missions, and no difference was existed between the main pilot and co-pilot in terms of the type of mission; however, a difference was existed in terms of the number of flights in each type of mission. In this study, the time-slots in which pilots execute their missions are defined as sorties. There were six sorties per day, and pilots could fly a maximum of two per day. Pilot efficiency could be checked using the Individual Pilot Competency Management (IPCM) system. The IPCM states the proficiency and qualifications of a pilot. It is also used to determine which missions are required to achieve or maintain a pilot's qualification. If a pilot fails to manage his or her IPCM, restrictions to which missions they can participate in arise. In this paper, mission efficiency was scaled from 0 to 10 with the IPCM in accordance with the urgency of each pilot's missions. A higher number indicated a more urgent mission.

On the basis of the IPCM, pilots are assigned to each mission or night duty as either the main pilot or co-pilot. Pilots also perform night duties in rotation. Night duty begins at 6:00 pm and finishes at 8:00 am the next morning. In light of pilot fatigue and safety factors, pilots do not fly on the day following the night duty. There is a specified turn around time for pilots and aircraft. For pilots, the turn around time is the time required to prepare for the next mission, as well as the downtime for rest following a mission. For aircraft, the downtime includes the maintenance after a flight completion. The turn around time for a pilot is two sorties and one for an aircraft. Using the information above and the assumptions stated below, we developed an optimized mathematical model. The basic assumptions are as follows:

1) Mission cancelations due to poor weather were not considered. This is different from real life, however as indicated in Section 2 schedules were updated weekly, allowing for canceled missions to be made up for in the future.
2) Flight schedules are often modified according to the changing will of the Wing or Group Commanders. This model does not incorporate this unpredictable situation.
3) Aircraft are always available, with maintenance conducted during turn around times and after flight completion.
4) The availability of pilots is known in advance.
5) There are no weekend missions, but there is night duty.
6) There are no additional missions aside from those indicated in advance.

3.2 Mathematical Model

<Notation>

- I : Set of total pilots
- I^m : Set of main pilots
- I^c : Set of co-pilots
- J : Set of total aircraft
- K : Set of total missions
- L : Set of total available flight days
- W : Set of total weeks
- M : Set of total available flight sorties
- e_{ik} : Efficiency of pilot i's working on mission k
- r_k^m : Monthly requirement of main pilot of mission k
- r_k^c : Monthly requirement of co-pilot of mission k
- p_{il}^{max} : Maximum number of sorties for pilot i on day l
- p_i^{max} : Maximum number of sorties for pilot i per week
- a_{jl}^{max} : Maximum number of sorties for aircraft j on day l
- a_j^{min} : Minimum number of sorties for aircraft j per week
- $c_{il} = \begin{cases} 1 & \text{if pilot } i \text{ is available on day } l \\ 0 & \text{otherwise} \end{cases}$
- $d_{il} = \begin{cases} 1 & \text{if pilot } i \text{ works on night duty on day } l \\ 0 & \text{otherwise} \end{cases}$
- $o_{jl} = \begin{cases} 1 & \text{if aircraft } j \text{ is assigned for emergency on day } l \\ 0 & \text{otherwise} \end{cases}$

<Decision Variable>

The decision variable of this study must specify who will fly with which aircraft and work on which mission and for which sortie. Therefore, we set up the decision variable as binary and defined it as follows :

- $x_{ijklm} = \begin{cases} 1 & \text{if pilot } i \text{ flies with aircraft } j \text{ working on mission } k \text{ on day } l \text{ at sortie } m \\ 0 & \text{otherwise} \end{cases}$

<Mathematical Model>

$$\max \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M} e_{ik}\cdot x_{ijklm} \quad (1)$$

$s.t.$

$$\sum_{i\in I^m} x_{ijklm} \le 1, \quad \forall j\in J, k\in K, l\in L, m\in M \quad (2)$$

$$\sum_{i\in I^s} x_{ijklm} \le 1, \quad \forall j\in J, k\in K, l\in L, m\in M \quad (3)$$

$$\sum_{i\in I^m} x_{ijklm} = \sum_{i\in I^c} x_{ijklm}, \quad \forall j\in J, k\in K, l\in L, m\in M \quad (4)$$

$$\sum_{j\in J}\sum_{k\in K} x_{ijklm} \le 1, \quad \forall i\in I, l\in L, m\in M \quad (5)$$

$$\sum_{j\in J}\sum_{k\in K} x_{ijklm} \le 1 - \sum_{j\in J}\sum_{k\in K} x_{ijkl(m+1)}, \quad \forall i\in I, l\in L, m\in M\backslash\{6^{th} sortie\} \quad (6)$$

$$\sum_{j\in J}\sum_{k\in K} x_{ijklm} \le 1 - \sum_{j\in J}\sum_{k\in K} x_{ijkl(m+2)}, \quad \forall i\in I, l\in L, m\in M\backslash\{5, 6^{th} sortie\} \quad (7)$$

$$\sum_{i\in I}\sum_{k\in K} x_{ijklm} \le 2 - \sum_{i\in I}\sum_{k\in K} x_{ijkl(m+1)}, \quad \forall j\in J, l\in L, m\in M\backslash\{6^{th} sortie\} \quad (8)$$

$$\sum_{i\in I}\sum_{k\in K} x_{ijklm} \le 2\cdot a_{jl}^{max} \times (1 - o_{jl}), \quad \forall j\in J, l\in L, m\in M \quad (9)$$

$$\sum_{j\in J}\sum_{k\in K}\sum_{m\in M} x_{ijklm} \le p_{il}^{max}\cdot c_{il}, \quad \forall i\in I, l\in L \quad (10)$$

$$\sum_{j\in J}\sum_{k\in K}\sum_{m\in M} x_{ijk(l+1)m} \le p_{il}^{max} \times (1 - d_{il}), \quad \forall i\in I, l\in L\backslash\{Last\ day\} \quad (11)$$

$$\sum_{j\in J}\sum_{l\in L}\sum_{m\in M} x_{ijklm} \ge r_k^m, \quad \forall i\in I^m, k\in K \quad (12)$$

$$\sum_{j\in J}\sum_{l\in L}\sum_{m\in M} x_{ijklm} \ge r_k^c, \quad \forall i\in I^c, k\in K \quad (13)$$

$$\sum_{j\in J}\sum_{k\in K}\sum_{l\in W}\sum_{m\in M} x_{ijklm} \le p_i^{max}, \quad \forall i\in I \quad (14)$$

$$\sum_{i\in I}\sum_{k\in K}\sum_{l\in W}\sum_{m\in M} x_{ijklm} \ge 2\cdot a_j^{min}, \quad \forall j\in J \quad (15)$$

The objective function (1) maximizes the total mission efficiency of the pilots for the entire schedule. Constraints (2) and (3) guarantee that for each aircraft, mission, day, and sortie, one main pilot and one co-pilot at most can be assigned. An inequality was adopted rather than an equality as there were sorties to which no mission was assigned. Constraint (4) guarantees that, for each aircraft, mission, day, and sortie, the number of main pilots and co-pilots must be equal. If no main pilot is assigned to a mission, no co-pilot is assigned either, and if a main pilot is assigned to a mission, a co-pilot is also assigned. Constraint (5) guarantees that, for each pilot, day, and sortie, at most one mission with one aircraft is assigned. Constraints (6) and (7) guarantee a turn around time for each pilot, day, and sortie. If a pilot conducted a mission for an arbitrary sortie m, he or she cannot work on sortie $m+1$ and $m+2$. If a pilot worked on sortie 5 or 6 (the last two sorties of the day), this does not prevent him or her from working the next day's sortie 1 or 2, as the constraints apply on each day. Constraint (8) guarantees a turn around time for each aircraft, day, and sortie. Similar to constraint (6), if an aircraft is used on a mission for an arbitrary sortie m, it cannot be used on sortie $m+1$. As two pilots fly together, $\sum_{i \in I}\sum_{k \in K} x_{ijkl(m+1)}$ was subtracted from 2. Constraint (9) guarantees that for each aircraft, day, and sortie, aircraft that are not assigned for an emergency can be used. The right-hand side of this constraint is multiplied by $2 \cdot a_{jl}^{max}$. a_{jl}^{max} indicates the maximum number of sorties for aircraft j on day l. Every aircraft is operated by one main pilot and one co-pilot; thus, for this reason, the right-hand side is multiplied by $2 \cdot a_{jl}^{max}$. Constraint (10) guarantees that, for each pilot and day, at most p_{il}^{max} missions can be executed if pilot i is available on day l. If pilot i is not available on day l, the right-hand side becomes 0, indicating no missions for day l. In pilot availability, leave, business trips, and physical issues are considered. Constraint (11) guarantees that, for each pilot and day, at most p_{il}^{max} missions can be executed for that arbitrary day $l+1$ if pilot i did not perform night duty the previous day l. If the pilot worked night duty on day l, the right-hand side becomes 0, indicating no mission on day $l+1$. Constraints (12) and (13) guarantee that, for each pilot and mission, the monthly requirements for each mission must be satisfied according to the position of the pilot (main pilot or co-pilot). Constraint (14) guarantees that for each pilot, at most p_i^{max} missions can be assigned per week. These constraints were added to prevent overwork for pilots. Constraint (15) guarantees that for each aircraft, at least a_j^{min} missions should be assigned per week. Similar to constraint (9), the right-hand side is multiplied by 2, which means that every aircraft is operated by a main pilot and co-pilot. These constraints were added to avoid the event that no mission is assigned to a specific aircraft. Utilization is a daily concept and is one of the most important factors that should be considered when making a schedule. It denotes the number of aircraft operated divided by the total number of aircraft. Using these constraints, the utilization of aircraft can be guaranteed to at least a certain degree.

4. Computational Results

<Table 1> shows pilot and aircraft information. The first row indicates the days, and the first column indicates the pilots and aircraft. Rows a to j of <Table 1> indicate the main pilots, and rows k to q indicate the co-pilots. Both the main pilots and co-pilots perform night duties. D indicates that the pilot is on night duty, whereas N indicates that they are not available. The last five rows correspond to the aircraft, where E indicates that the aircraft is assigned for emergency use only. The cells where pilots and aircraft are unavailable are highlighted in yellow. As pilots are not available on days that follow night duty, that day is also highlighted in yellow.

<Table 1> Information of Pilots and Aircraft

D : Duty, N : Not Available, E : Emergency

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Main Pilot	*a*	D			N		N					D			
	b		D										D		N
	c			D				N			N			D	
	d				D						N				D
	e	N				D			N				N	N	
	f	N					D								
	g							D							
	h					N	N		D		N		N		
	i	N								D					N
	j	N					N	N			D				
Co Pilot	*k*	D			N				D						
	l		D				N			D		N		N	
	m			D							D			N	N
	n				D							D			
	o		N			D							D		
	p		N		N		D		N					D	
	q	N	N					D					N		D
Air craft	*1*	E					E					E			
	2		E					E					E		
	3			E					E					E	
	4				E					E					E
	5					E					E				

The model was solved using Python-Gurobi, and the results are as follows. Our model produced a 1-month schedule; however, it can be used to produce more than that. But for the sake of simplicity and readability, only 2 weeks' worth of the schedule are presented in <Table 2>.

We compared our model's solution with several other feasible schedules. The average objective value of feasible schedules was 1405, whereas the objective value of our model's schedule was 2066, which indicates an improvement of nearly 47%. <Table 2> presents the results of the model. The sortie is written in the form of "number–number." The first number indicates week, and the latter indicates sortie. For each assigned sortie, the main pilot and co-pilot are matched one to one. The turn around time worked for both pilots and aircraft. For instance, pilots *d* and *l* flew on Monday in the first sortie of the first week. No mission was given to them for the second and third sorties, and they then had another mission for the fourth. For the aircraft, the turn around time was only one sortie. Aircraft 5 was used on Monday for the first sortie of the first week. It was not used in the second sortie of that day but was used for another mission on the third sortie. The pilots who were unavailable on an arbitrary day could not fly. For instance, pilots *e*, *f*, *i*, *j*, and *q* were not available on day 1. Accordingly, they could not fly on Monday of the first week. Pilots who performed night duties did not work the next day. Pilots *a* and *k* had duties on day 1, which means no work on day 2. Likewise, pilots *b* and *l* had their night duties on day 2, which means no work on day 3. The aircraft that were assigned for emergency use did not have normal missions on that day. Aircraft 1 to 5 were assigned for emergencies from the first to the fifth days, respectively. As can be seen from <Table 2>, no aircraft was assigned a normal mission from Monday to Friday on the first week. In this schedule, p_i^{max} was set to 7. Pilot *o* worked the most, with seven sorties in the first week, and pilots *b*, *k*, *o*, and *p* worked the most overall, with seven sorties in the second week. In this schedule, a_j^{min} was set to 3. Aircraft 3 and 5 were used the least in the first week, with six sorties, whereas aircraft 2 and 4 were used the least in the second week, with eight sorties. Consequently, at least four aircraft were used every day, ensuring at least 80% utilization.

<Table 2> Optimized Flight Schedule

MAIN : Main Pilot, CO : Co Pilot, ACFT : Aircraft, MSN : Mission

day / sortie	Mon				Tue				Wed				Thu				Fri			
	MAIN	CO	ACFT	MSN	MAIN	CO	ACFT	MSN	MAIN	CO	ACFT	MSN	MAIN	CO	ACFT	MSN	MAIN	CO	ACFT	MSN
1-1	*d*	*m*	3	B	*b*	*l*	1	F	*f*	*k*	2	B					*j*	*o*	3	C
	h	*l*	5	A	*h*	*n*	3	E	*h*	*p*	5	E								
1-2	*b*	*p*	2	E					*d*	*m*	4	B	*e*	*o*	3	E	*a*	*k*	4	A
									e	*o*	1	E	*g*	*n*	1	A	*e*	*q*	2	F
1-3	*a*	*o*	5	F	*g*	*m*	5	B									*b*	*p*	1	E
	g	*n*	4	A																
1-4	*d*	*l*	3	B	*b*	*n*	4	A									*c*	*o*	2	D
1-5	*b*	*p*	5	E					*d*	*o*	2	B	*e*	*o*	2	E	*f*	*k*	1	D
	h	*m*	4	E					*h*	*p*	4	E	*g*	*n*	1	A				
1-6	*c*	*n*	2	B	*f*	*m*	4	C	*e*	*k*	1	D					*b*	*q*	3	F
					h	*l*	1	B	*j*	*m*	5	B					*e*	*p*	2	D
2-1	*f*	*n*	4	A	*b*	*o*	1	E	*b*	*o*	2	E	*a*	*k*	5	B	*d*	*o*	3	B
	i	*k*	1	D	*d*	*l*	3	B	*g*	*k*	3	D	*h*	*p*	4	E	*f*	*l*	5	E
2-2	*d*	*m*	2	B	*a*	*q*	2	F	*j*	*q*	1	D	*i*	*q*	2	F	*g*	*m*	1	B
	h	*o*	5	E	*c*	*m*	5	B												
2-3					*i*	*n*	1	A	*e*	*p*	4	E	*b*	*n*	3	A	*b*	*k*	4	C
																	j	*p*	5	E
2-4					*d*	*p*	3	A												
2-5	*b*	*m*	1	B	*a*	*q*	5	C	*a*	*o*	3	E	*h*	*q*	2	E	*f*	*m*	5	F
	d	*n*	4	A	*b*	*m*	1	B	*g*	*q*	1	F	*i*	*p*	4	B	*g*	*o*	3	C
2-6	*a*	*k*	5	D	*c*	*n*	3	C	*b*	*p*	4	E	*a*	*k*	5	D	*d*	*l*	1	D
	h	*o*	2	E	*i*	*l*	2	C	*e*	*k*	2	F	*g*	*n*	3	F	*j*	*p*	4	F

5. Conclusion

This study aimed to plan monthly flight schedules for the Air Force considering pilot efficiency, monthly requirements, duties, emergencies, and turn around times. Using this approach, we were able to automatically and efficiently generate monthly schedules rather than employing a daily approach. Potential future research and limitations are as follows.

First, our model could be improved by including uncertainties, such as weather conditions, like those found in Schaefer's work [10]. Second, the development of a method for measuring the fatigue level of pilots would be desirable. In this study, we restricted the maximum number of flights per day and week to guarantee pilot downtime. However, if we were to develop a method that could forecast the fatigue level of pilots based on past data, we would be able to improve scheduling for each pilot.

This model could be utilized with other flight squadrons by incorporating their unique characteristics. In real-world scenarios, circumstances often change with very little forewarning, thus forcing pre-made schedules to be modified. Whenever such events occur, scheduling officers must devise other reasonable schedules. Even if the Air Force uses our methodology, pre-made schedules will often need to be modified. However, we believe that our study can be utilized as a strong starting point and convenient ways of making them. Considering the number of scheduling officers in the world, we hope that this study can help reduce their workload and contribute to the operational progress of the Air Force.

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