

Identifying aircraft and personnel needs to meet on-station patrol requirements ☆

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Abstract. Determining the required number of aircraft and personnel to maintain a given presence on station is a common and important problem in military contexts. In this paper, the proposed approach consists of finding schedules for multiple aircraft that meet the on-station requirement while minimizing the number of aircraft and crews required. Specifically, after discussing the schedule for a single aircraft, an integer program for the multiple aircraft case is formulated and presented. To capture the effect of unplanned maintenance on the overall number of required aircraft, a parameterized serviceability model is also introduced. As illustrated by a case study, this easy to implement methodology is able to provide quick and insightful results to the decision makers.

Keywords: scheduling; integer programming; serviceability

Introduction

To deploy aircraft from a base to patrol an area is an integral part of the mandate of any air force. Being able to do so, however, requires not only a sufficient number of serviceable aircraft stationed at the base, but also enough personnel to fly and maintain the aircraft. This interconnectedness is often overlooked when acquiring aircraft. Instead, the focus is often placed on the number of aircraft required, which may not be the limiting factor in meeting the overall requirement.

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The problem considered here does not entail assigning individual aircraft to specific flight segments, as it is commonly the case in the airline industry (Qi *et al.* 2004). Instead, the aim is to find a joint aircraft-crew cyclic schedule that provides persistent coverage of the patrol area. In addition, unlike Kim *et al.* (2013), details of how the surveillance is conducted once the aircraft are on-station are also omitted; the interest is in determining the number of aircraft and personnel necessary to maintain a given on-station presence given crew and maintenance constraints. As a result, the nature of the problem is closer to that of personnel scheduling, specifically nurse scheduling (Bertsimas and Tsitsiklis 1997; Ferrand *et al.* 1997; Burke *et al.* 2004; Van den Bergh *et al.* 2013; Ernst *et al.* 2004), than it is to those used in the airline industry.

This paper proposes a methodology that jointly explores the number of aircraft and personnel necessary to maintain a given number of aircraft on station in a patrol area at all times for a 24-hr period. Specifically, a scheduling problem is formulated to optimize the times at which aircraft are operating on station while satisfying crew-rest requirements and meeting maintenance constraints over the course of a 24-hr period.

The remainder of this paper is organized as follows. An overview of the proposed scheduling model is presented in the next two sections, with the first section covering the scheduling of a single aircraft and the second presenting the integer program used to schedule multiple aircraft. This is followed by a treatment of unplanned maintenance, which is parameterized using the aircraft serviceability. A simple case study is then presented to illustrate the methodology before concluding.

Scheduling a single aircraft

Within its endurance envelope (i.e., the time it can fly before its fuel remaining requires it to return to base) an aircraft must transit from its base to the patrol area, perform its activities on station, and return to base and land. Each aircraft schedule is thus viewed as a sequence of non-overlapping activities, with the level of granularity limiting the detail of activities to those that affect the length of time an aircraft is on station either directly (through activities that consume endurance) or indirectly (through activities such as daily maintenance). Aircraft activities, including planned maintenance considered for the scheduling effort are described in Table 1, which also lists their impact on endurance and their durations for the case study described below.

Although the schedule is developed on a 24-hour clock, this sequence of activities is not always 24 hours. It is assumed that each aircraft is assigned a certain number of Aviation Units (AU), an AU being a complement of personnel that are required to fly and maintain an aircraft. When more than one AU are assigned to a single aircraft, it is assumed that all AU perform the same set of activities in the same order, which leads to an intrinsic period of repeating activities of less than 24 hours for that particular aircraft. For example, the case study presented below assumes that up to two AU can be assigned to any aircraft. Thus, if two AU are assigned to an aircraft, then two sequences of activities, each of 12 hours, will occur in a given 24-hour block leading to a schedule for the aircraft repeating on a daily basis as required.

Table 1. Description of aircraft activities.

<i>Activity</i>	<i>Description</i>	<i>Impacts Endurance</i>	<i>Duration (minutes)</i>
In hangar	Aircraft idle in hangar.	N	Variable
Stage and launch	Activities before the start of the flying operations.	N	60
Shutdown and stow	Activities following the end of the flying operations.	N	45
Maintenance check	Systems checks.	Y	120
Transit	Travelling to and from patrol area.	Y	15
On station	Time an aircraft is on station.	Y	Variable
Approach and landing	Final approach and landing.	Y	10
Turnaround	Activities after landing and before taking off again.	N	30

The time that an AU works in any 24-hour period, defined herein as the Duty Shift, cannot exceed some maximum number of hours. For example, in the case study discussed below, this will be set to 14 hours per day. The Duty Shift starts with the aircraft in the hangar, so the first activity is to go through the stage and launch sequence. This is followed by a block of time during which flying operations take place, after which the aircraft is shut down and stowed in the hangar, run through the maintenance check, and parked in the hangar until the next scheduled shift.

The block of time during which flying operations take place is limited by the maximum possible length of the Duty Shift. It is comprised of a set of Flying Cycles, where each cycle involves a specific chain of activities: the aircraft leaves the base and transits to the patrol area, operates on station, transits back to the base, completes the approach and landing sequence, and for all but the last Flying Cycle in the block, undergoes a turnaround sequence, which includes activities such as refuelling, crew change, downloading or uploading mission data, etc.

In scheduling Flying Cycles, it is assumed that an aircraft will remain on station as long as allowed by its endurance, the one possible exception being for the last Flying Cycle in a Duty Shift. Defining a Flying Cycle that uses the entire endurance of the aircraft as a full Flying Cycle, scheduling proceeds by fitting as many full Flying Cycles as possible into the available block of time during which flying operations take place. In most cases, this process leaves an unused portion of time at the end of the block. If the duration of this portion is long enough for the aircraft to transit to and from the patrol area, to spend some time on station, and to complete the approach and landing sequence, then an additional Flying Cycle is scheduled, with the time on station limited to what can be permitted by the time available within the block. If the unused portion is not long enough for such an activity, then the aircraft is stowed in the hangar so the maintenance check can commence. In this latter case, the resultant Duty Shift is shortened accordingly. The time from when

the aircraft is first launched after exiting the hangar until the commencement of the shutdown and stow process is referred to as the Flying Shift.

The following sequence of activities then summarizes how the schedule of a single aircraft is generated:

1. At the beginning of the Duty Shift, the aircraft undergoes the preparatory stage and launch period as it is removed from its hangar, prepared, and launched;
2. Once the stage and launch period is completed, the following repeating pattern, which constitutes a Flying Cycle, consumes the Flying Shift:
 - a. Transit from the base to the patrol area;
 - b. Remain on station as endurance and the Flying Shift permit;
 - c. Transit from the patrol area to the base;
 - d. Undergo the approach sequence and land; and
 - e. If another sortie is planned, resupply the aircraft and change the flying crew during the turnaround;
3. At the end of the Flying Shift, AU members shut down the aircraft and stow it in the hangar;
4. In the hangar, the aircraft undergoes its maintenance check; and
5. The aircraft remains parked in the hangar until the next scheduled Duty Shift.

Scheduling multiple aircraft: An integer program approach

It is assumed that the start time of each aircraft schedule is arbitrary within the day, that is one could start at midnight, while another at midday or any other time in between. This freedom allows one to find an optimal schedule for an aircraft fleet by staggering several single aircraft schedules, as in the nurse scheduling problem (Bertsimas and Tsitsiklis 1997; Ferrand *et al.* 1997; Burke *et al.* 2004; Ernst *et al.* 2004) and is implemented using integer programming.

To write down the integer program (IP), both the absolute time and possible start times for a schedule are discretized. Specifically, the set of time indices is referred to as I while the set of start-time indices is referred to as J . Formalizing the optimization problem further requires accounting for the fact that aircraft are operated by AU. In what follows, an l -AU aircraft refers to an aircraft operated by l AU and each non-negative integer $(x_l)_j$ tracks the number of l -AU aircraft schedules starting at time index $j \in J$.

To manage the number of aircraft on station, the approach used is to define a constraint at each time step $i \in I$. This involves introducing the number of aircraft an l -AU aircraft schedule starting at start-time index j will deliver on station at time i , $(A_l)_{ij} \in \{0,1\}$, and the number of aircraft desired on station at time i , b_i . Each matrix A_l is of dimension $|I| \times |J|$ and the j -th column of A_l corresponds to the on-station contribution of an aircraft schedule beginning at start-time index j .

With this, the IP formulation is then:

$$\begin{aligned}
& \text{minimize} && \sum_{l \in L} \sum_{j \in J} (x_l)_j \\
& \text{subject to} && \sum_{j \in J} (A_l)_{ij} (x_l)_j \geq b_i, \quad \forall l \in L, \\
& && \sum_{j \in J} (x_l)_j \leq n_l^{\max}, \quad \forall l \in L, \\
& && (x_l)_j \in \mathbb{N}_0
\end{aligned}$$

where the set of l -AU aircraft types allowed is L and the second constraint is introduced to partially or fully specify the numbers of l -AU aircraft operating from the base (n_l^{\max} being the maximum number of a l -AU aircraft allowed).

Accounting for serviceability

In optimizing the schedules, the model described above makes the unrealistic assumption that the aircraft are always available when needed, which is equivalent to them never experiencing a system failure and, thus, undergoing unplanned maintenance. In reality not all aircraft will be available at any given time. If one defines a serviceable aircraft as one that does not require unplanned maintenance, then it becomes necessary to make a distinction between serviceable and unserviceable aircraft.

An immediate consequence of introducing serviceability is that maintaining aircraft on station is now contingent on a random process, i.e., unplanned maintenance. This entails that the relevant evaluation metric becomes a probability, namely the probability of meeting the requirement. The possibility of unplanned maintenance also implies that using only the scheduling model discussed above is impossible, as it assumes a steady and repeating schedule that neglects this possibility. Thus, if one wishes to consider the effects of unplanned maintenance, what has been described to this point is insufficient.

One option would be to develop a fully stochastic model that explicitly examined unplanned maintenance (Marlow and Novak 2013; Mattila *et al.* 2008). Instead, here, a serviceability model is introduced that neglects the interplay between planned and unplanned activities at the scheduling level, and returns the probability of having sufficient serviceable aircraft to meet the requirement given the total number of aircraft stationed at the base. The result is then taken as an estimate of the probability of meeting the requirement.

To assess the effect of serviceability on meeting the requirement, the following approach is used. First, the probability that exactly k aircraft are serviceable is found by solving a $M/M/n_{ac}$ queuing model with a finite calling population (Hillier and Lieberman 1990). This yields a binomial distribution with parameters n_{ac} and s , the total number of aircraft stationed at the base and the serviceability rate, respectively (as in Marlow and Novak 2013). Next, if one assumes that, for the number of available AU, the base needs at least

k_{min} serviceable aircraft to maintain the requirement, e.g., maintaining one or more aircraft on station at all times, then the probability of meeting this requirement is estimated using the cumulative probability of having at least k_{min} serviceable aircraft that is:

$$P = \sum_{k=k_{min}}^{n_{ac}} \binom{n_{ac}}{k} s^k (1-s)^{n_{ac}-k}.$$

Remark this assumes that when an aircraft becomes unserviceable, the AU can be assigned to different aircraft. Considering serviceability in the absence of this assumption is more complicated and beyond the scope of this paper.

Case study

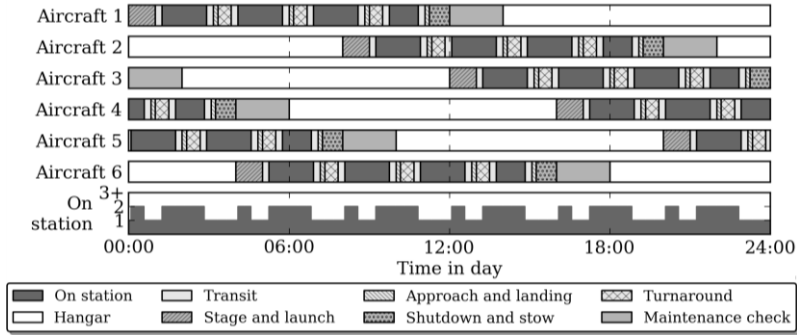
For this case study the objective is to maintain one aircraft on station at all times over the course of a 24-hr period, i.e., $b_i = 1, \forall i \in I$. Moreover, each aircraft is operated by either one or two AU, and each AU cannot work more than 14 hours per day. Given that the durations listed in Table 1 are all multiples of five minutes, the time discretization is set to five minutes and to restrict the size of the problem to solve, the possible start times for each schedule are set to multiples of 30 minutes. The aircraft endurance is also assumed to be 140 minutes.

Figure 1 displays two examples of a multi-aircraft schedule found by solving the IP with different constraints on the numbers of l -AU aircraft allowed. As expected, in both cases, the threshold requirement of maintaining one or more aircraft on station at all times is met. Figure 1a displays a schedule that necessitates six aircraft, where each aircraft is operated by one AU, while Figure 1b presents a five-aircraft schedule, where four aircraft are operated by one AU and one aircraft is operated by two.

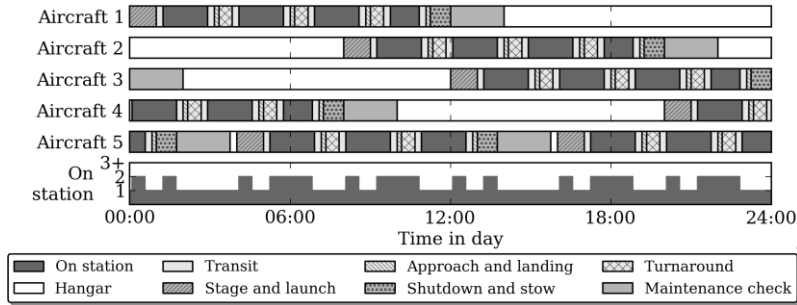
By repeatedly solving the IP with varying constraints on the maximum numbers of l -AU aircraft allowed, it is then possible to trace a boundary in the aircraft-AU space between the region where it is possible to meet the requirement and another where it is not. For the case at hand, to maintain one or more aircraft on station at all times requires having at least three serviceable aircraft and six AU stationed at the base.

Solving the IP only identifies how many aircraft must be serviceable in order to maintain at least a certain number of aircraft on station at all times. If the aircraft never experienced a system failure and, thus, never required unplanned maintenance, then those values would be representative of the number of aircraft that would need to be stationed at the base. In reality, however, both will occur.

For this case study, an 85% serviceability rate is assumed. Figure 2 reports the probability of maintaining at least one aircraft on station at all times and shows that when serviceability is considered, having three aircraft and six AU is not necessarily sufficient to ensure one aircraft on station at all times. To have, for example, at least a 90% probability of meeting the requirement, it becomes necessary to have at least five aircraft stationed at the base and six AU.



(a) Schedule with six aircraft and six AU and where each aircraft is assigned one AU.



(b) Schedule with five aircraft and six AU and where the last aircraft is assigned two AU.

Fig. 1. Two sample schedules.

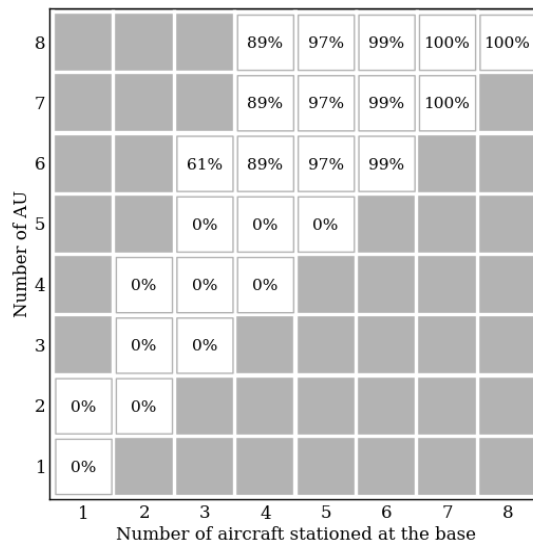


Fig. 2. Probability of maintaining one aircraft on station at all times given an 85% serviceability rate.

Conclusion

This paper modelled a repeating 24-hour period of operations. The factors related to crew fatigue, longer periodic maintenance inspections, impact of adverse weather, major system maintenance, or attrition were not modelled but each on their own would raise concerns about the capacity to maintain the required level of intensity for a number of days, weeks or even possibly months as may be required. Additionally, air traffic congestion resulting in one or more aircraft being unable to depart or land at a given time was not considered, but may well be a limiting factor, especially when a large number of aircraft are operating from the same base.

A more detailed consideration of these factors and others would produce results that are both more realistic and most likely more demanding in terms of the materiel and personnel resources needed to maintain the aircraft on station. An exception may be efficiency found by breaking down an AU into its constituent parts and having the maintainers service more than one aircraft.

This paper presented a simple, yet informative, methodology to determine the number of aircraft and personnel required to maintain a given number of aircraft on station in a patrol area. After presenting the scheduling model for a single aircraft, an integer program was formulated, the solutions of which are schedules for a fleet of aircraft operating from the same base and able to meet the requirement. To account for unplanned maintenance without having recourse to a full blown stochastic model, a parameterized serviceability model was introduced. As exemplified, the methodology is able to provide quick and insightful results for decision makers.

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