An Optimization Method of Controller Scheduling at Small and Medium-sized Airports Based on Fatigue Analysis

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Abstract. In recent years, a number of aviation accidents have caused the social attention to aviation safety. The serious shortage of controllers at China's small and medium-sized airports has become an important hidden danger of aviation accidents. It is necessary to make a scientific and reasonable scheduling scheme in order to solve this problem. Based on civil aviation air traffic management rules to the controllers workload, this article proposes a linear programming method to analysis of China's small and medium-sized airport controllers scheduling model. At the same time, the fatigue factor is accounted into and the model is solved by 0-1 integer programming. Using an actual case data from Wanzhou Airport, the proposed method satisfies the needs of the airport and reduce controllers work fatigue to achieve a win-win results.

Overview

With the rapid development of China's civil aviation industry, the corresponding flight volume increases rapidly, resulting in a surge in the workload of controllers. According to statistics, in 2017, China's civil aviation industry completed a total turnover of 108.308 billion tons of kilometers. As a result, the huge workload causes physical and psychological fatigue. There has been a shortage of controllers in small and medium airports all over the country which has a great impact on the aviation safety of our country such as unreasonable schedules, heavy workload, etc. Therefore, on the premise of considering fatigue factors, it is very important to optimize the mode of controller scheduling for small and medium-sized airports in China.

Status Analysis

Foreign studies on controller fatigue started earlier. For example, in 1971, foreign scholar Grandjean confirmed that controller fatigue working time was more than 6 hours and night work aggravated fatigue state through percussion test and flash test [1]. In BOIVINDB's study, it was confirmed that the sleep time, sleep quality and sleep amount of shift workers are affected by circadian rhythm [2]. Zhen LIU proposed to analyze and judge the fatigue level based on the controller's response to the ground and air calls [3]. Hui-bin JIN confirmed and analyzed the effect of fatigue on work by using biological analysis method [4]. However, most of the above discussions just based on preliminary perceptual knowledge, without systematic solutions and with low compatibility with the actual work.

And in the mode of the controller's scheduling, China has implemented a double duty policies. At the same time, many people are also optimizing the typesetting method. For example, Li-li Wang improved the scheduling method on the premise of justice [5]. In terms of shift mode, Jiao Zhang also carried out relevant analysis on the two schemes of upper two days off and upper one day off, and reached a better conclusion of the former by limiting different conditions [6]. However, there is still a big gap in the theory of scheduling optimization.
Controller Fatigue Problem

Establishment of fatigue model. In the 2018 Zhen Liu's *Quantitative evaluation model of fatigue risk based on the voice response of controllers*, the fatigue risk model of controllers was established by studying the voice response of controllers and using the method of probability and statistics. This section will expand the related introduction based on the research results.

Calculated fatigue risk. Generally speaking, the quantitative evaluation of risk is determined by the possibility of risk occurrence and the loss after risk occurrence. Therefore, the quantitative evaluation model of fatigue risk of controllers can be considered according to this idea, that is, the fatigue risk is jointly determined by the possibility of occurrence of fatigue and the loss of fatigue, if $R_{FT}$ is the risk value of fatigue event; $P_{FT}$ is the possibility of occurrence of fatigue events; $C_{FT}$ is the severity of fatigue event, then $R_{FT} = C_{FT} \times P_{FT}$. For a given normal probability density distribution function $f(x)$, if the mean value of the controller's response time in a duty period is $\mu$, the closer it is to the overall expected value, the less likely the controller will have fatigue risk. Therefore, in this model, the probability of fatigue event of this controller is represented by the probability of regional probability $P(x \in [2\mu - \mu, \mu])$ with the expected value of the distribution function as the axis of symmetry $\mu$ and the distance as the axis of symmetry $\mu$. Therefore, $P_{FT}$ the calculation formula is as follows:

$$P_{FT} = \left\{\begin{array}{ll}
\frac{2}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\mu} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) dx & , \mu > \mu \\
0, & , \mu \leq \mu
\end{array}\right.$$  

(1)

Where, $0 < P_{FT} < 1$.

The deviation between the mean value $\mu$, of the response time of the controller in a certain duty period and the overall expected value $\mu$ is shown as follows: the farther from the overall expected value $\mu$, the more serious the fatigue event is. The calculation formula of severity is:

$$C_{FT} = \frac{\mu - \mu}{\sigma} , \mu > \mu$$

$$C_{FT} = 0, \mu \leq \mu$$

(2)

Where, $C_{FT} > 0$.

Fatigue risk level. According to the nature of the normal distribution curve, 99.7% of the data will fall within 3 standard deviations of the population expected value, so most values of $C_{FT}$ are between 0 and 3. Meanwhile, according to principle 3 $\sigma$ of normal distribution, namely:

$$P(\mu - \sigma < X \leq \mu + \sigma) = 68.3\%$$

$$P(\mu - 2\sigma < X \leq \mu + 2\sigma) = 95.4\%$$

$$P(\mu - 3\sigma < X \leq \mu + 3\sigma) = 99.7\%$$

The respective value $P_{FT}$ ranges are reasonably divided, and the fatigue risk level is classified according to equation $R_{FT} = P_{FT} \times C_{FT}$, as shown in table 1:
According to the value $R_{ft}$ range, the fatigue risk level of the controller is divided into 5 levels.

When the risk level in I–III, thinking that the controllers in the current work period fatigue risk is in an acceptable range; When the risk level in IV level or V level, control unit should be on duty controllers appropriate intervention, take rest or work shifts, to effectively reduce the risk of fatigue of the controller.

When the controller fatigue problem is considered together with the controller scheduling optimization problem, the controller fatigue level can be divided according to the length of continuous duty of the controller and matched with the controller fatigue risk level, as shown in table 2:

<table>
<thead>
<tr>
<th>Accumulated duty time in two consecutive days(h)</th>
<th>0~8</th>
<th>8~12</th>
<th>12~14</th>
<th>14~20</th>
<th>&gt;20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{ft}$</td>
<td>0~0.68</td>
<td>0.68~1.98</td>
<td>1.98~2.97</td>
<td>2.97~3</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Risk level</td>
<td>I (No fatigue)</td>
<td>II Mild fatigue</td>
<td>III (fatigue)</td>
<td>IV (Severe fatigue)</td>
<td>V (over fatigue)</td>
</tr>
</tbody>
</table>

Effects of fatigue. For the controller: it is easy to have bad emotions such as impatience and irritability, which will lead to confusion of thoughts, inattention, and affect individual work efficiency. From the medical point of view, long-term irregular work and rest, will make the probability of health diseases, including sleep disorders, headaches and other conditions, and even lead to cardiovascular disease.

Team matching: the controller is unstable, which indirectly affects the coordination and cooperation among team members. As a whole, the team will lead to a decrease in work efficiency, an increase in work error rate and an increase in instruction risk.

Aviation operation: under fatigue condition, the controller cannot fully monitor the repetition of the flight crew, and the normal operation order is affected, or even chaos occurs; In case of emergency, cannot get fast and accurate instructions, extend the rescue time, so that the occurrence of disaster.

Establishment of Scheduling Model

Controller scheduling is essentially a problem of optimal allocation of controllers to meet the requirements of civil aviation air traffic management rules (CCAR-93-R5) and shift constraints. However, in actual scheduling, people often take into account factors such as team resource management, controller fatigue and airport flight flow, so as to produce a schedule that meets many different conditions. Therefore, this paper will use linear programming as a means to establish a scheduling optimization model based on the fatigue analysis of controllers, in order to solve the problem of insufficient controllers in small and medium-sized airports.

Mandatory Constraints in Linear Programming. This paper focuses on the controllers of small and medium-sized airports. The main mode of control is procedure control, and most of the schedules are two shifts. Therefore, before establishing the controller scheduling model, the following key assumptions are established:

(1) The mode of airport control is procedure control;
(2) two shifts a day, each shift does not exceed 8 hours;
control seats and coordination seats are exchanged every 4 hours in one shift;

a scheduling period has 31 days;

According to the key assumptions and CCAR-93-R5, the compulsory constraint (HC) in CCAR-93-R5 can be simplified as follows:

HC1: Controllers shall not be allowed to work continuously for more than 10 hours.
HC2: Controllers shall not be on duty for more than 40 hours within one calendar week.
HC3: The control unit shall arrange a rest period of at least 24 consecutive hours for the controller within seven consecutive calendar days.

In addition to the compulsory constraints in CCAR-93-R5, human factors are an important factor affecting aviation safety management, which directly affects the safety of air transport. Among them, the fatigue effect of controllers is particularly important. According to the results of Zhen Liu's "Quantitative Assessment Model of Fatigue Risk Based on Controller's Speech Response Time" in 2018, the following constraints are established:

HC4: When the risk level is between I and III, it is considered that the fatigue risk of the controller is within acceptable range during the current working period.

According to the actual situation of different small and medium-sized airports, the restrictions on the number of people on duty are different. The following restrictions are established:

HC5: The number of person on duty is no less than P per shift;

Parameter Hypothesis and Model Algorithms. $X_{ijk}$ means that the first controller arranges the K shift on the j-day.

C=$\{1,2,..., N\}$ denotes a collection of n controllers;
D=$\{1,2,..., Q\}$ denotes the set of Q days in a scheduling cycle;
K=$\{1,2\}$ denotes class k of the day.

The magnitude of fatigue risk $R_{FT}$ is equal to the product of probability $P_{FT}$ and severity $C_{FT}$ of fatigue occurrence, i.e. $R_{FT} = P_{FT} \times C_{FT}$

CS is a set of scheduling schemes satisfying all strong constraints. The set of rules and restrictions HCR includes HC1, HC2, HC3, HC5, and the set of fatigue restrictions HCF includes HC4.

Based on the parameters defined above, we establish the following controller scheduling model:

HC1: $\sum_{k=1}^{2} X_{ijk} = 1, \forall i \in C, \forall j \in D$  (3)

HC2: $\sum_{j=1}^{7} \sum_{k=1}^{2} X_{ijk} \leq 5, \forall i \in C, \forall j \in D$  (4)

HC3: $\sum_{j}^{i+6} \sum_{k=1}^{2} X_{ijk} \leq 6, \forall i \in C, \forall j \in [1,q-6]$  (5)

HC4: $R_{FT} \leq 2.97$  (6)

HC5: $\sum_{l=1}^{n} X_{ijk} \geq P, \forall i \in C, \forall j \in D$  (7)

In the model of controller scheduling algorithm, the stipulations in CCAR-93-R5 (HC1, HC2, HC3) must be satisfied, and the fatigue constraints (HC4) should be satisfied as far as possible. Different small and medium-sized airports can adjust the constraints in HC5 according to the number of controllers on each shift in order to achieve a more reasonable distribution of human
resources. The upper limit of fatigue value can also be changed according to the different requirements of the control unit for the fatigue degree of the controller. Generally speaking, the lower the fatigue limit, the lower the pressure of controllers will be, the higher the aviation safety index will be, but the number of controllers will be increased.

**Case Computing and Solution**

**Case Data.** Controller data in this paper are derived from the schedule of a small and medium-sized airport. At present, there are nine licensed controllers in that airport control office, which implement the system of alternate duty of one last rest and two last rest. The working hours are divided into two periods: the first flight to 14:00 and 13:50 to the final flight. After the handover procedure is completed, the handover personnel should overlap for ten minutes on their posts. When the control room arranges tower duty, there shall be no fewer than two controllers with airport control license, one is responsible for control command and the other is responsible for control monitoring and coordination; when the tower controller is on duty for six hours continuously, two controllers exchange seats;

On the premise that the original conditions of the airport remain unchanged, the original schedule is optimized by branch-and-bound method on MATLAB, and a new schedule is obtained.

**Analysis of optimization results.** Set the number of violations for the i-controller in a scheduling cycle to be $T_{io}$, severe fatigue times to be $T_{if}$, total number of violations to be $T_o$, total severe fatigue times to be $T_f$.

$$T_o = \sum_{i=1}^{n} T_{io}$$

$$T_f = \sum_{i=1}^{n} T_{if}$$

After calculating the total number of violations of the original schedule $T_o=31$, and the total number of violations after the optimization of the model $T_o=0$; the number of severely tired people in the traditional scheduling plan $T_f=58$, after the optimization of the model into the model optimization to obtain the severe fatigue $T_f=15$. Thus, after the optimization of the model, the total number of violations decreased by 100 percent, while the total number of severe fatigue decreased by 74.13 percent.

Therefore, this model achieves the goal of making the scheduling plan strictly comply with the relevant regulations of the bureau, and at the same time greatly reducing the amount of risk caused by fatigue, thus improving the aviation safety factor.

**Summary**

Based on fatigue analysis, the optimal scheduling model for small and medium-sized airport controllers is a new model which takes the fatigue factors that affecting aviation safety into consideration. The parameters can be adjusted according to the actual conditions of different small and medium-sized airports, which has great applicability. It has great significance for solving the problem of lack of controllers in small and medium airports, and also has considerable reference value for future controllers scheduling program design.

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References


