An Optimization of Airline Scheduling Systems Based on a New Airline Pilots' Fatigue Assessment Algorithm

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Abstract. Flight safety reports from different sources indicate that the proportion of accidents caused by flight fatigue accounts for 6-11% of all types of flight accidents. Current regulations in the civil aviation industry across the world generally emphasize the length of working hours rather than the influences of circadian rhythm disorders. Based on an analysis of the flight mission data of 567 pilots in 2019, which highlighted the associations between circadian rhythm disorders and flight fatigue, we have proposed a new algorithm to reflect pilots' fatigue status to include five main indicators: actual working hours, circadian rhythm disorders, work rhythm disorder, altitude flight hours and flight crew composition. The results assessed by the new algorithm reported that about 70% of the airline pilots studied were under the threat of a high risk of fatigue in 2019. Subsequently, this research suggests the use of two algorithms to optimize pilot scheduling systems, and findings show that the percentage of pilots with a high level of fatigue can be largely reduced. **Keywords:** Airline pilots, Circadian rhythm disorder, Fatigue load, Scheduling algorithm.

1 Introduction

1.1 Background

Although the number of air accidents each year is low compared with other forms of transport, with continued long-term annual increases in civil aviation aviation safety cannot be said to not need continuous attention [1]. According to data from Flightera.net, while the number of daily flights in the past three years is lower than for 2019, before the outbreak of the COVID-19 pandemic, the volume of flights has increased year by year[1]. Under the impact of the epidemic, travel demands are much lower than before; however, travel requirements are much higher, and the demands for comfort, health and safety are growing. Moreover, recent research shows that travel by air is still preferred by the public [2]. It has been said that the air demands will recover in 2–6 years [3]. However, how demand for air travel will change post COVID-19 is still an unanswered question. Air travel might not improve significantly in the near future under the impact of restrictions from domestic and international [4]. But flight safety must always be under discussion.

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[1]Flightera.[Online] Available:https://www.flightera.net/en/flight_stats

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1.2 Pilot Fatigue

To a large extent flight safety has greatly improved with the upgrading of flight equipment [5]. Intelligence and automation have been gradually applied to aircraft equipment, and this has greatly reduced air accidents. However, the reduction rate has slowed down in recent years. Pilots, as an essential human element, play an important role in flight safety. In addition to facing complicated flight tasks and irregular schedules, pilots have to cope with problems such as shift work and sleep loss, which result in pilot fatigue. Studies have shown that human error is the main cause of more than 70% of aviation accidents [6]. Therefore, alleviating pilot fatigue should greatly reduce the occurrence of flight accidents.

The International Civil Aviation Organization (ICAO) associates crew member fatigue with sleep loss, extended wakefulness, circadian phases and workload (mental and/or physical activity). A review of the literature on pilot fatigue reveals that many factors may lead to fatigue, including subjective factors such as a person's physical condition and biological clock, and objective factors such as scheduling systems, the flying environment, temperature, light, etc. Among these factors, circadian rhythm and sleep quality were highlighted by most scholars [7]. Therefore, building risk management systems to avoid aircrew fatigue is usually related to the above factors, and the break times between flight duties, working time and flight crew composition [8] are thought to be closely related to pilot fatigue.

1.3 Limitations of Pilot Fatigue Assessment Systems

Researchers use subjective and objective tools to assess pilot fatigue, such as rating scales and actigraphy [9]. Fatigue Risk Management Systems (FRMS) are widely used in fatigue management, which depends on schedules to evaluate fatigue levels [10]. However, due to regulatory and legislative requirements, formal policies and procedures for FRMS cannot be implemented [11]. The Civil Aviation Administration uses flight hours, altitude flight hours and flight crew composition to measure fatigue levels. Although the data are generally available, some factors, including circadian rhythm disorders and actual working time, are not considered. Therefore, building an implementable and reasonable fatigue assessment system that incorporates these factors is crucial.

1.4 Aims and Overview of the Study

Our paper seeks to present a framework supported by real-world data with subjective and objective parameters to analyse the fatigue level of pilots. By analysing the disadvantages of present scheduling systems, and by evaluating the current knowledge regarding pilots' fatigue, we try to optimize the scheduling system and provide valuable suggestions and methods for enterprise scheduling.

2 Methods

2.1 Notations

The subsequent notations are used in the presented model.
(1) Indices
Z : Objective function.
k : Index for the pilots ($k = 1, 2, 3$).
i : Index for flight route.
(2) Sets

K : Set of pilots.
L : Set of task cycle numbers.
P : Set of pilots who will not fly high altitude areas.
I : Set of flight routes.
I_k : Set of pilot k's flight.
R : Set of flight days.

(3) Parameters

i_h : High altitude flights.
i_d : The first flight of one day.
i_k : The flight of pilot k.
r_k : The flight days of pilot k.
t_i : The flight hour of flights.
t_{hi} : The flight hour of high altitude flights.
M : The flight routes of three-flight crews.
m : The flights of three-flight crews.
N : The flight routes of two-flight crews.
n : The flights of two-flight crews.
i_{y1} : Frequently delayed flights.
i_{y0} : Infrequently delayed flights.
S_i : The origin of flight i.
E_i : The final destination of flight i.
w_z : The score of circadian rhythm disorder.
w_j : The score of working rhythm.
f_{id} : The work schedule category score for a flight.
j_{id} : The score of change trend of working types in adjacent two days.
g_l^k : Time of pilot k in the l task cycle.
b_{jn} : The 0−1 decision variable: Flight j takes off on the n^{th} day as 1 and does not take off on the n^{th} day as 0.
d_l^k : The departure airport number of pilot k in the l task cycle.
$d_l^{k'}$: The arrival airport number of pilot k in the l task cycle.
$\overline{d^k}$: The base of pilot k.
d_i : The departure airport number of flight i.
$d_i^{'}$: The arrival airport number of flight i.
x_{ki} : Decision variable i = 0, 1, and if x_{ki}=1 means pilot k in flight i, x_{ki}=0 means not.

(4) Quantification of circadian rhythm disorder

As the main cause of pilot fatigue, quantifying circadian rhythm disorder is crucial in building a pilot fatigue assessment [12]. Because of the variable times of flight duties, pilots' working hours are quite different to those of normal people, and a long-term, non-standard schedule brings severe circadian rhythm disorder [13]. Therefore, classifying the first duty time of a day can be helpful in distinguishing the degree of circadian disorder. In one study it was proposed that standard working hours should begin at 9 am and 5 pm, while beginning at 9 pm and ending at 5 am is considered to be completely non-standard working hours [14]. Mikeal divided the flight duty into five periods depending on the time that pilots arrive at the airport [15]. A literature search, Delphi studies, interviews with pilots, and a pilot study were used in identifying indicators. Each type and assigned score can be found in table 1.

(5) Quantification of working circadian rhythm

Due to the specifications of their job, most civil pilots face not only circadian rhythm disorder, but also working circadian rhythm disorder. Different from insufficient sleep caused by circadian rhythm disorder, working circadian rhythm is brought on by frequent shift work in two adjacent days. Research has shown that working circadian rhythm disorder is considered

Table 1. Arranging type and corresponding score

kind	type	definition	score
1	early morning	Pilots arrive at the airport between 3am and 6am.	2
2	morning	Pilots arrive at the airport between 6am and 8am.	1
3	day	Pilots arrive at the airport between 8am and 9pm.	0
4	evening	Pilots arrive at the airport between 9pm and 11pm.	1
5	night	Pilots arrive at the airport between 11pm and 3am.	2

Table 2. The type of working circadian rhythm disorder and corresponding score

Changing type	The definition of changing type	Score
1	There was no work or the same type of work arrangement in the adjacent two days.	0
2	In the adjacent two days, one day has a flight duty, while another day does not.	1
3	In the adjacent two days, the work arrangement is a cross arrangement (kind 1 & kind 2, kind 2 & kind 3, etc.)	2
4	In the adjacent two days, the work arrangement is a cross two arrangement (kind 1 & kind 3, kind 2 & kind 4, etc.)	3
5	In the adjacent two days, the work arrangement is a cross three arrangement (kind 1 & kind 4, kind 2 & kind 5, etc.)	4
6	In the adjacent two days, the work arrangement is a cross four arrangement (kind 1 & kind 5).	5

to be the main cause of pilot fatigue [16]. As we know, frequent changes in someone's work shift can easily result in fatigue. For example, if pilots start to work in the early morning of the first day, starting to work at night on the next day will be much more tiring than starting to work again in the early morning. Therefore, in measuring the level of working circadian rhythm disorder, work shift span within two days is taken into consideration. A big span will result in greater fatigue during work. The scores of the different types are shown in table 2.

2.2 Study 1

This study is based on the fatigue risk formula of the Civil Aviation Administration, taking circadian rhythm disorder and working circadian rhythm into consideration. Thus the circadian rhythm disorders, working rhythm, altitude flight hours, flight hours and flight crew composition are all included in the formulae. The entropy weights method is applied in building the fatigue assessment formula, which is based on the data of 567 pilots selected by a civil aviation company in 2019.

In constructing the fatigue risk assessment system, five indicators−flight duration, altitude flight hours, circadian rhythm disorder, working rhythm disorder and crew configuration−are included. By using SPSSAU analysis software, different factors will be computed in forward or reverse directions; the data from forward processing include actual working hours, circadian rhythm disorder, working rhythm disorder and high altitude flight time; the data from reverse processing are the flight crew composition. The formulae are:

$$x_{MMS,ij} = \frac{x_{ij} - min\left(x_{1j}, x_{2j}, ...x_{nj}\right)}{max\left(x_{1j}, x_{2j}, ...x_{nj}\right) - min\left(x_{1j}, x_{2j}, ...x_{nj}\right)}. \tag{1}$$

$$x_{NMMS,ij} = \frac{max\left(x_{1j}, x_{2j}, ...x_{nj}\right) - x_{ij}}{max\left(x_{1j}, x_{2j}, ...x_{nj}\right) - min\left(x_{1j}, x_{2j}, ...x_{nj}\right)}. \tag{2}$$

Table 3. Coefficient weight of five indicators

Item	Information entropy value	Information utility value	Weight coefficient
Average flight crew composition	0.87	0.13	17.63%
Daily score of circadian rhythm disorders	0.82	0.18	24.74%
Daily score of working rhythm	0.82	0.18	24.68%
Daily flight hours	0.88	0.12	16.77%
Daily altitude flight hours	0.89	0.12	16.19%

$$x_{MC,ij} = \frac{x_{ij}}{\overline{x_{ij}}}. \tag{3}$$

The five indicators were applied in an entropy weight calculation by SPSSAU. The calculation process is as follows, where n is the number of the index, and m means the number of the sample:

$$R = \left(r_{ij}\right)_{n\times m} i = 1, 2, 3, ..., n, j = 1, 2, ..., m. \tag{4}$$

$$P = \left(p_{ij}\right)_{n\times m} P_{ij} = \frac{r_{ij}}{\sum_{j=1}^{m} r_{ij}}. \tag{5}$$

$$u_i = \frac{-\sum_{j=1}^{m} P_{ij} ln P_{ij}}{lnm}. \tag{6}$$

$$w_i = \frac{1 - u_i}{\sum_{i=1}^{n} 1 - u_i}. \tag{7}$$

According to the entropy weight calculation, the weight of every factor was computed. The most important factor was the daily score of circadian rhythm disorders, while the altitude flight hours was the least significant. The details are shown in table 3.

In conclusion, the flight fatigue assessment (FFA) formulae is

$$FFA = 0.18c + 0.25a + 0.25b + 0.17d + 0.16e$$

In this formulae, a represents the score of circadian rhythm disorders, b represents the score of working rhythm, c is the score of flight crew composition, d is the score of flight hours, and e is the score of flight hours.

2.3 Study 2

In study 2, we use two algorithms to optimize pilot scheduling. Specifically, we use the objective function, aiming to reduce flight fatigue in weekly scheduling and match reality. Considering the constraints of flight costs and benefits, we chose flight hours, altitude flight hours, circadian rhythm disorders and working rhythm from the above formulae to assess the flight fatigue of scheduling. At the same time, the cost of the overall task cycle is the lowest possible, and the task cycle duration between crews is balanced as far as possible.

(1) Objective functions

In a flight task cycle, the flight hours (FH) and altitude flight hours (AFH) can be obtained by adding up the pilot k's flying hours in flight i. And the score of circadian rhythm disorders (w_z) and working rhythm (w_j) will be calculated by adding the score of each type of categories, which are showed in table 1 and table 2. These formulae are

$$FH = \sum_i t_i x_{ki}. \tag{8}$$

$$AFH = \sum_i t_{hi} x_{ki}. \tag{9}$$

$$w_z = \sum_{i \in i_d} f_i. \tag{10}$$

$$w_j = \sum_{i \in i_d} j_i. \tag{11}$$

The constraints of the objective function are classified into two parts. Firstly, there are some rules for flight companies that should be strictly implemented, such as requiring the weekly flying to be less than 40 hours,

$$\sum_i t_i x_{ki} \leq 40, \forall \mathrm{k}. \tag{12}$$

The weekly working time should be no more than 60 hours,

$$\sum_i (t_i + 1.5) x_{ik} \leq 60, \forall k. \tag{13}$$

Another part is about crew allocation. Delay will lengthen the working time for pilots, which might increase pilots' fatigue. Therefore, in arranging the pilots for every flight, we basically relied on the airlines' frequency of late arrivals and whether the flight was via the high altitude area. For example, if the flight airlines delay more often than others or fly in high altitude areas, which might bring more fatigue risk to pilots, we might allocate three crews in these kind of flights. Therefore, three crews are allocated in high altitude area or frequently delay flights, and two crews are for normal flights,

$$3m + 2n = k \tag{14}$$

All the pilots include those who can finish high altitude flights *(l)* and who cannot (p),

$$l + p = k. \tag{15}$$

According to the data of the flight company, we find that only 40% of pilots can do high altitude flying,

$$l \leq 0.4k. \tag{16}$$

The flying time should not be longer than nine hours, which are included within the constraints for flying time and crew arrangements,

$$\sum_{i} t_{hi} x_{ki} \leq 9, \forall k. \tag{17}$$

The pilots who cannot fly at high altitude area are accounted for by setting

$$x_{pih} = 0. \tag{18}$$

The ideal flying task cycle considered to be the destination of the last flight is the take-off location of the next flight for one pilot, which might shorten the working time for pilots. Therefore, each pilot's task cycle will include a continuous period of time.

$$\sum_{n \in N} h_{nl}^{k} \left(1 - h_{n-1,l}^{k}\right) \leq 1, \forall l \in L, k \in K. \tag{19}$$

$$\sum_{n \in N} h_{n-1,l}^{k} \left(1 - h_{n,l}^{k}\right) \leq 1, \forall l \in L, k \in K. \tag{20}$$

A pilot is only allocated one task cycle per day,

$$\sum_{l \in L} h_{nl}^{k} = 1, \forall n \in N, k \in K. \tag{21}$$

The departure airport (d_l^k) for the first flight and the arrival airport ($d_l^{k'}$) for the last flight in each task cycle are given by

$$\begin{aligned} d_l^k &= \sum_{n \in N} h_{nl}^{k} \left(1 - h_{n-1,l}^{k}\right) \left(\sum_{i \in I} x_{ij}^{k} b_{jn} \left(1 - b_{in}\right) d_j\right) \\ d_l^{k'} &= \sum_{n \in \mathcal{N}} h_{nl}^{k} \left(1 - h_{n+1,l}^{k}\right) \left(\sum_{j \in I} x_{ij}^{k} b_{in} \left(1 - b_{jn}\right) d_i'\right) \end{aligned}, \forall l \in L, k \in K \tag{22}$$

The first flight in each task cycle must start from the base, and the last must return to the base:

$$\begin{cases} d_l^k \left(d_l^k - \overline{d^k}\right) = 0 \\ d_l^{k'} \left(d_l^{k'} - \overline{d^k}\right) = 0 \end{cases}, \forall k \in K, l \in L \tag{23}$$

The total duration of the crew in one task cycle is given as

$$g_l^k = \sum_{n\in N} h_{nl}^k \left(1 - h_{n+1,l}^k\right)\left(\sum_{i\in I}\sum_{j\in I} x_{ij}^k b_{in}\left(1 - b_{jn}\right) t_i^{'}\right) - \sum_{n\in N} h_{nl}^k \left(1 - h_{n-1,l}^k\right)\left(\sum_{i\in I}\sum_{j\in I} x_{ij}^k b_{jn}\left(1 - b_{in}\right) t_j\right)$$
$$\forall l \in L, k \in K. \tag{24}$$

The total duration of each task cycle for each crew shall not exceed *MaxTAFB* minutes

$$\sum_{l\in L} g_l^k \leq MAX\text{TAFB}, \forall k \in K \tag{25}$$

Each crew shall have at least *MinVacDay* days off between two adjacent task cycle

$$\sum_{n\in N} h_{nl}^k \left(1 - h_{n-1,l}^k\right) n - \sum_{n\in N} h_{n-1,l-1}^k \left(1 - h_{n,l-1}^k\right) n \geq MinVacDay, \forall k \in K, l \in L. \tag{26}$$

Finally each crew member shall be left for no more than*MaxSuccOn* days of continuous duty

$$\sum_{n\in N} u_{n-1}^k \left(1 - u_n^k\right) n - \sum_{n\in N} u_n^k \left(1 - u_{n-1}^k\right) n \leq MaxSuccOn, \forall k \in Kl \in L \tag{27}$$

Therefore, the objective function and constraints are

$$Min(Z) = \sum_k \frac{b_1 \sum_i t_i x_{ki} + b_2 \sum_i t_{hi} x_{ki} + b_3 w_z + b_4 w_j}{k\ r_k}. \tag{28}$$

(2) Algorithms

Two algorithms are used in optimizing pilot scheduling, and both of them are under the constraints above (Equations 12−27). The first algorithm is used to reduce the individual fatigue index of pilots by rearranging pilots on the original flights. The second algorithm is used to create a flight task cycle that includes some flights which are parts of whole flights in 2019 and fit the constraints of one specific task cycle. Every pilot can choose one flight task cycle. The flight task cycles can cover all flights that the airlines need. Now, we will discuss the two algorithms specifically.

The first step of the first algorithm is to arrange flights by time in the first day. After that, we choose the first flights. Next, we find the closest flight that has the departure place that is the same as the arrival place of first flights. We combine these two flights into one flight line. Then we choose the next closest flight that has the start place that is the same as the end place of the flight line. We add that flight into the fight line. We repeat this step until all flights are in flight lines. The third step is to arrange pilots to cover every flight line. The fourth step is to repeat the three steps for each day. The fifth step is to calculate the individual fatigue index of pilots. Finally, we repeat the five steps to find the minimum index.

The first step of the second algorithm is sorting every flight to make the flight cycle and give different jobs to different pilots. The second step is to decide which pilots to fly. The

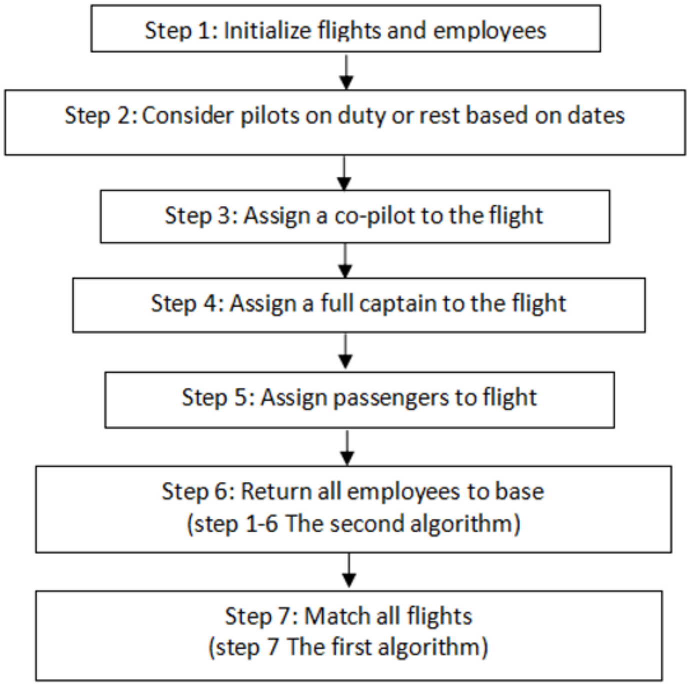

Figure 1. Individual steps in the algorithm for assigning flight cycle to pilots

Table 4. The weights of each indices

Item	Entropy	Weights of indices
Daily score of circadian rhythm disorder	0.82	30.03%
Daily score of working rhythm	0.82	29.96%
Daily working time	0.88	20.36%
Daily time on high altitude flying	0.88	29.65%

third step is to choose the captain, co-pilot and staff for each flight. Finally, we use flights to form the flight task cycles. The detailed steps are shown in Figure 1.

Under the constraints of the rules, costs and other aspects, we used the objective function with the entropy weight method,

$$Min(Z) = \sum_k \frac{0.2\sum_i t_i x_{ki} + 0.2\sum_i t_{hi} x_{ki} + 0.3 w_z + 0.3 w_j}{k r_k}. \tag{29}$$

3 Results

3.1 Pilots' Fatigue

According to the degree of circadian rhythm disorder criteria identified by Wang [13], we find that 38.8% were reported to have pilots with severe circadian rhythm disorder. Over one third

Table 5. The basic state of circadian rhythm disorders in flight routes

Degree of circadian rhythm disorder	Duty time	The amount of flight routes	Ratio
Complete disorder	9 pm to 5 am of next day	30681	38.80%
Mild disorder	5 am to 9 am and 5 pm to 9 pm	13140	16.60%
Disorder	9 am to 5 pm	35205	44.60%

Table 6. The average score of each category before and after scheduling

Item	Old schedule	New schedule
Average flight crew composition	2.88	2.7
Daily score of circadian rhythm disorders	0.98	0.52
Daily score of working rhythm	1.5	0.58
Daily flight hours	5.64	1.18
Daily altitude flight hours	0.57	0.07

Table 7. Comparison of unified scores of all categories before and after scheduling

Unified item	Old schedule	New schedule
Score of flight hours	0.49	0.07
Score of altitude flight hours	0.113	0.046
Score of circadian rhythm	0.19	0.12
Score of working rhythm	0.126	0.072

of flight routes (see table 5 for specific indicators) confirms the crucial impact of circadian rhythm disorder.

The comprehensive fatigue score of the pilots, according to the new fatigue risk assessment formulae, can be calculated. Among them, the lowest score was 0.09, while the highest score was 0.73, and 33% of the pilots were at a higher risk of fatigue while 67% of the pilots were at lower level.

3.2 Scheduling Optimization

In comparing the results before and after the new scheduling, the items like circadian rhythm disorder and working rhythm disorder has greatly improved. Under the new scheduling arrangement, pilots can finish flight tasks with less working time. Therefore, taking flight task cycle into consideration might be helpful to reduce the pilots' fatigue. Details of the data are shown in table 6.

In order to assess the changes of different factors, we use the unified score of each category, a way to convert data into dimensionless scores describing the overall situation of the pilot, and which can standardize the different categories. In the comparison of the results between the two schedules, every factor improves. The details are shown in table 7.

The fatigue risk index of the first two weeks is calculated, and the comparison of fatigue coefficient of pilots before and after the new scheduling is shown in table 8.

From the data in table 8, it appears that the number of pilots with a high fatigue risk decreased from 356 to 96. This is a significant decrease, and demonstrates that the new scheduling rules are effective in improving the rate of fatigue.

Table 8. Comparison of the number of fatigued pilots

Unified item	Old schedule	New schedule
Pilots in high fatigue risk	356	96
Pilots in normal fatigue risk	211	471
Average fatigue risk	0.34	0.33

4 Discussion

4.1 Working Rhythm and Circadian Rhythm Disorders Play an Important Part in Fatigue Assessment

Working rhythm and circadian rhythm disorders, based on our paper and previous studies, are important factors affecting flight fatigue. Traditional fatigue evaluation ignores the influence of rhythm disorder on pilots, focusing only on the flight times. Therefore, it is beneficial to consider the influence of rhythm disorder on flight fatigue.

4.2 A Proper Scheduling for Pilots Should be Made by Civil Aviation Companies

For the scheduling management of pilots, airlines should apply a more humanized and safer scheduling mechanism that will satisfy their basic operations at the same time. Arranging more reasonable flight tasks and reducing flight fatigue by reasonable measures as well as carrying out flight fatigue risk assessment regularly will ensure greater flight safety for everyone.

5 Conclusion

Based on the one-year data of civil aviation pilots' fatigue status, this paper conducted an in-depth study on flight fatigue in the aviation industry. Through the quantitative analysis of pilot fatigue, it is found that over a half of pilots are in a state of high fatigue risk. This is a problem whose solution is critically important for civil aviation companies.

After identifying five factors that might affect pilots' flight fatigue, a pilot scheduling model based on fatigue was constructed to help reduce the fatigue of pilots, and which will be helpful in reducing the fatigue risk down to a controllable state. The results presented here, which were based on the fatigue risk assessment, have proven that the new scheduling system can help in reducing fatigue. Both circadian rhythm disorders and working rhythm were considered, and this improved the effectiveness of the new model. The final result gives a new way of assessing pilots' fatigue and of optimizing scheduling based on this.

All procedures performed in studies involving human participants were in accordance with ethical standards of Sichuan University medical committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards [2022-No.1529].

The researchers informed all participants of the full content of the experiment, and they signed the informed consent form before the experiment.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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