Operational planning of aircraft routes when servicing a random stream of requests arriving during the flight

V I Goncharenko¹,², G N Lebedev¹, D S Martynkevich¹ and A V Rumakina¹

¹ Department of Automatic and Intelligent Control Systems, Moscow Aviation Institute (National Research University), 4, Volokolamskoe shosse, Moscow, 125993, Russia
² V A Trapeznikov Institute of Control Sciences of Russian Academy of Sciences, 65, ul. Profsoyuznaya, Moscow, 117997, Russia

E-mail: goncharenkovi@mai.ru

Abstract. The process of servicing ground facilities with a group of aircraft is being considered when there is a flow of flight requests. The problem of parametric optimization is posed in the selection of the number of aircraft based on the multiplicative form of a single efficiency criterion. It is shown that the solution of this problem is possible with the help of the queuing theory, according to which the system under consideration belongs to the class of multi-channel queuing systems with waiting. The inventive method for developing an operational planning algorithm is based on a combination of sequentially executed ranking operations in order to ensure the lowest operational costs based on a minimax criterion in the worst conditions in terms of service delay time. A simulation program has been developed that provides an analysis of various dispatching algorithms, as well as determining at each step the number of free requests and the number of available and occupied aircraft. Along with the choice of the most effective algorithm for operational planning of aircraft routes, the task of assigning the required number of aircraft is solved.

1. Introduction

Currently, civil and unmanned aviation carry out air traffic according to a pre-prepared plan—either according to the flight schedule according to the unchanged schedule, or according to the prepared flight task before the next flight. At the same time, there are a number of practically important tasks of routing a group flight, when pre-flight planning is carried out only for the beginning of a group flight, and then new requests are served already during the flight. In particular, in civil manned aviation, when flying to emergency areas, operational planning of a multidimensional route flight is required when new information about the places of emergency situations and the routes of movement of ground rescue services is received. In the same mode, the search should be carried out for mobile groups or vehicles that require their detection, moving along different routes, when, depending on the current information received, it is necessary to quickly reschedule the flight.

A special perspective for manned small aircraft is the “air taxi” mode, when there is no constant demand between “permanent” airports, which is met according to the schedule, and requests are received for flights to destinations whose composition is random and unknown in...
advance [1]. For Russia, there is a huge need for this in areas of the country where ground transportation is extremely difficult (taiga in Siberia and the Far East, mountainous terrain in the Caucasus, Altai, etc.), and local air traffic over short distances is extremely necessary.

The same significance is represented by the considered mode for unmanned aircraft, in particular, designed for monitoring both stationary and mobile objects. In this case, often there is a situation when the received video information significantly alters the importance of the upcoming scheduled observation points, and the structure of consumer information and the nature of their new filings in advance is unpredictable, which eliminates group air operations according to plan.

In other words, the organization of a group flight when servicing requests received “on call” during the flight is an urgent and promising task of air traffic control. The analysis of publications in this subject area shows:

- despite the fact that the organization of air traffic of small aircraft in the absence of pre-flight planning when servicing unpredictable call requests is becoming a dominant factor, this task is not paid due attention;
- it is important to solve the problem of air traffic management for a mixed group of manned and unmanned aircraft both at the pre-flight planning stage and in the process of directly performing its target tasks, but there are currently no constructive mathematical models describing the dynamics of changing its space-time states [2–9].

2. Formulation of the problem

The following starting conditions have been adopted for the task.

1. It is believed that the source of the formation of flight tasks is a random flow of requests received during the flight, which are considered for two cases. In the first case of manned aviation use, each application contains the known coordinates \( x_i, z_i \) of the initial point of departure and \( x_j, z_j \) of the final point of arrival when landing in each service. At the same time moment of the request appearance \( t_j \) is distributed according to the law of Poisson with known probability density [10]. It is also accepted that the distances \( r_{ij} \) between points of flight are also subject to the Poisson law of distribution. In the second case of the use of unmanned aerial vehicles for the delivery of cargo and the monitoring of land points, the coordinates \( x_j, z_j \) of these points are also known, with the probable allocation of \( t_j \) points of the appearance of applications under the Poisson law. A common feature of both cases is the requirement to give higher value to servicing not only those requisitions that originated earlier, but also the proximity of the destination to the aircraft.

2. A group of similar aircraft is given, the number \( N \) of which is either predefined or its optimal value is to be found. In both manned and unmanned aerial applications, the velocity \( V \) and altitude \( H \) of the flight are considered constant and predetermined. Therefore, the time of \( \Delta t_{ij} \) flight from one point to another is entirely determined by the distance \( r_{ij} \) between them.

3. The current coordinates \( x_k, z_k \) of the aircraft’s location and the coordinates \( x_j, z_j \) of the serviced points are considered known.

Taking all the above assumptions and factors into account, the task requires to propose a new approach to the problem of operational planning of aircraft routes taking into account the listed factors and constraints and to evaluate its effectiveness by comparison with known ones group action dispatch algorithms.

3. The proposed approach to solving the problem of operational planning of aircraft routes

Along with the choice of the most effective algorithm for operational planning of aircraft routes, the assignment of the required number of aircraft also plays an important role. So, in manned
aviation, in the absence of a regular schedule of arrivals and departures, but with a known flow of applications with an average speed of $\lambda$, it is sometimes necessary to choose such a number $N$ to ensure the optimal combination of efficiency and speed of performing the desired set of flights. In unmanned aviation, it is also necessary to determine the optimal number of aircraft, taking into account the demand for regular observations of ground objects that occurs when updating video information.

The solution of this problem is possible with the help of the queuing theory, according to which the system under consideration belongs to the class of multi-channel queuing systems with expectation, when $N$ is the number of channels, in each of which one aircraft serves requests with an average speed of $\mu$.

The block diagram of the queuing system is shown in figure 1.

![Figure 1. Structure of the mass service system.](image)

According to figure 1 to the input of the system with $d$ the number of free channels, received a flood of applications with intensity $\lambda$, with some of them forms a queue of length $S$, and the rest of the application previously selected to this scheduling algorithm, serving aircraft, the number of which is equal to $(N - d)$, with rate $\mu$. As a result, the number of steps of discretization statistics is accumulated in the form of values is the average distance $r_{av}$ for flights from point $i$ to point $j$, which determines the service, medium length $S_{av}$ queue of orders that characterize the waiting time in the queue and the average number $l_{av}$ free channels, which determines the additional operating costs in the “idle”. These characteristics are sufficient to estimate the penalty functions in the form of additional operating costs $E$ and the total average service time $T$ of each application.

In order to compare different algorithms for operational planning of aircraft routes and estimate the optimal number of aircraft, the following block diagram of computer modeling is proposed, presented in figure 2.

According to the presented flowchart, the following designations are used for modeling:

- $i = 1, \ldots n$ is the number of the serviced ground station or application;
- $j = 1, \ldots N$ is the number of the aircraft selected for maintenance;
- $k = 1, \ldots n$ is the number of the current operational planning step during discretization.

The discretization step $k$ refers to the target allocation actions at any of the two moments when one of the aircraft is released from service, or when a new request for the necessary flight appears. At each step, the process of dispatching and performing flights is modeled using blocks 2–6, shown in figure 2.
Accordingly, at the input of the system, using block 1, the process of placing a set of ground points that are a potential source of applications on a given rectangular territory is modeled. In this case, the points are placed so that the distances between them are subject to Poisson’s law, and their number is $n \gg N$.

Next, at the current step $k$ (including the first one), the “random” moment of the request appearance in any of the points at time $t_k$, also corresponding to the Poisson distribution, is modeled. Then (taking into account the known number $j$ of the new application point, the coordinates $x_i, z_i$ of the current location of the aircraft and the determination in block 2 of the number $d$ of free aircraft and the number $S$ of other applications in the queue), the specified dispatching discipline is implemented in block 3, which determines the indication of the selected flight from point $i$ to point $j$.

This allows, with the help of the kinematic model of flights in block 4 and the calculation of the lost service time in block 5 to find an intermediate result of adherence to the plan at the $k$-step in the form of penalty functions of costs of $E_k$ and delay in servicing $T_k$ for those aircraft and applications that are involved in service as well as for other “free” applications and aircraft.

At any step $k$ of planning, a “random” moment is modeled for other variants of the source data. The developed simulation program is able to analyze various dispatching algorithms, as well as to determine at each step the number of free applications and the number of free and occupied aircraft.

The analysis of the effectiveness of the three main dispatching options adopted in computer modeling is carried out. As the simplest option 1 of single-criteria selection of the highest priority new request from several at $S > 1$ with one free aircraft at $d = 1$, the preference conditions are used in proportion to the time $\tau_i$ of waiting for requests in service on the principle of “the request came first—will be served first”. The advantage of this option is that the service time for the most important requests is minimized. However, there is a significant drawback—among the favorites there may be points with a significant distance from the group of the aircraft, which generally reduces the efficiency of a group flight. As option 2, another choice algorithm is possible based on a two-parameter criterion that takes into account both the importance of the selected point $\tau_i$ and its distance $r_{ij}$ from the i-free aircraft at the same time. According to this option, the expected flight time to the $j$-th point should be reduced, which means that the speed of processing requests will increase.

A comparison of service options 1 and 2 shows that in option 2, all indicators have improved, namely, the waiting time for requests, the “idle time” and the integral penalty function have decreased. At the same time, it is important that the optimal number of $N$ is reduced by 25%. However, option 2 does not take into account the fact that the proximity to the next destination of a free aircraft is less likely than one of several busy aircraft completing their service. Therefore,
a different approach to solving the problem is proposed below, which takes into account the degree of completion of servicing applications by occupied aircraft in option 3, and uses a special algorithm for target allocation based on the minimax criterion [5].

The initial concept of the proposed approach is the mandatory accounting for \( d > 0, \ S > 0 \), not only free, but also busy aircraft—at each planning step, all \( N \) considered aircraft are involved. This led to the fact that due to the rejection of the mandatory assignment for a new request of a free refusal, a situation will arise in future steps when at \( d > 1 \) and \( S > 1 \) queues will occur simultaneously, and as a rule, the values of \( d \) and \( S \) will not be equal to each other.

As a result, first there will be a subtask of assigning a priority set of applications and selected aircraft, both available and busy, if their number is equal to each other. After that, as a second action, the task of target distribution of the selected applications between the designated aircraft should be solved.

As a result, the following common approach to operational planning is proposed, based on the execution of two main actions—appointment at \( S > d \) at each step of a priority set of applications with their excess for the purpose of ranking them and choosing their part with the number, is equal to \( d \), or the assignment at \( S < d \) of a priority set of aircraft, both free and occupied, and the purpose of ranking their excess number and choosing their part with the number, is equal to \( \rho \). After that, the second action is performed—the target distribution of the selected applications among the assigned aircraft using a well-known algorithm, or a special one, described below [11–14].

To compare option 3 with options 1 and 2, a computer simulation of the application service system in the air taxi mode was performed. The simulation results are presented in table 1.

| \( N \) | \( X_1 \) | \( X_2 \) | \( X_3 \) | \( \Pi_1 \) | \( \Pi_2(1) \) | \( I_0(1) \) | \( I_0(2, 5) \) | \( I_0(2) \) |
|---|---|---|---|---|---|---|---|---|
| 3 | 267 | 12 | 490 | 590 | 379 | 223392 | 373 | 219949 |
| 4 | 236 | 59 | 40 | 140 | 396 | 55465 | 366 | 51295 |
| 5 | 195 | 173 | 9 | 109 | 468 | 51029 | 382 | 41603 |
| 6 | 157 | 273 | 0 | 100 | 530 | 53024 | 394 | 39385 |
| 7 | 130 | 334 | 0 | 100 | 564 | 56378 | 397 | 39695 |

From the obtained simulation results and the values of \( I_0(1) \) and \( I_0(2) \), it can be seen that the minimum of the integral penalty function presented below is provided at \( N = 5 \), which, in comparison with the previous option 2, provides a 20–25% reduction in operating costs by counting the aircraft engaged in maintenance [15].

4. Selection of the optimal number of aircraft using the integral penalty function

To evaluate the successful service, two penalty functions are calculated—the average waiting time \( \tau_{av} \), for the start of service of one request for different values of \( N \), as well as the total cost \( E \) of operating costs, consisting of the cost of aircraft downtime and the cost of the flight to the designated place of service of the request. In addition, a single indicator for evaluating the effectiveness of dispatching is required, depending on the selected number of \( N \) servicing aircraft. As this number increases, the value of \( \tau_{av} \) decreases, and the value of \( E \) increases.

The results of the calculations of the total idle time and the total waiting time of the request, depending on the selected dispatch criteria and the number of aircraft, are presented in figure 3.

The indicator of the achieved balance is the use of the multiplicative \( J_0 \) criterion, which minimizes the total penalty

\[
J_0 = \min(\tau_{av} + \tau_{min})(E + E_{min}).
\]
Figure 3. The results of calculations of the total idle time and the total waiting time for the application: (a) the total waiting time for applications; (b) the total flight time of the aircraft.

After completing the required number of service steps, the request flow at the end of the simulation evaluates the final value of the $J_0$ criterion for the given number $N$ and the assigned service discipline, after which the simulation is repeated for other options of the source data.

Thus, in contrast to the generally accepted simulation modeling in the theory of queuing, the proposed scheme is able to evaluate not only probabilistic characteristics, but also:

- to introduce various dispatching algorithms into the simulated system;
- simulate the processes of changing the importance of each time request at any planning step;
- determine the number of available aircraft, or the number of request waiting for service in the queue, and as a result distinguish between the “idle” and “peak” mode from each other;
- to quantify the advantages of the chosen application service discipline, when in the “peak” mode, priority points are the closest to the aircraft group, and in the “idle” mode the preference is given to the important though more remote points.

When modeling a group flight of aircraft, three disciplines of servicing the flow of applications were considered:

1. If the number $S$ of new applications is greater than one and one aircraft is released from service, then according to the queuing theory, the priority application is the one with the maximum waiting time $t_j$ in accordance with the criterion:

$$J_1 = \max_j \tau_j.$$  (2)
If one application is new, and the number of available aircraft is \( d > 1 \), then this application is served by the nearest aircraft according to a different criterion:

\[
J_2 = \min_i r_{ij}.
\]  

(3)

2. If the number of new applications \( S > 1 \), and one aircraft is released, then, in contrast to the criterion (1), the priority application takes into account not only the waiting time \( \tau_i \), but also the distance \( r_{ij} \) from the place \( j \) of its occurrence to the \( i \) aircraft:

\[
J_3 = \max_i \frac{\tau_j}{r_{ij}}.
\]

(4)

According to criterion (3), the flight time of the aircraft to the service point should be reduced, and, consequently, the speed of servicing applications will increase. In this case, it is assumed that in both cases free aircraft are used in the service, and the busy ones do not participate in the assignment process.

3. If there are busy aircraft in the vicinity of the origin of a new application that are completing their service, a special minimax criterion is used to determine the need of refraining from servicing, and then to use the busy aircraft, which will arrive at the place of a new application earlier than the free aircraft.

The optimal number of aircraft required to support a certain number of objects varies depending on the maintenance discipline. For the first option considered, the largest number of aircraft is required, for the second and third, the value decreases. In further studies, it is advisable to consider the application of various service disciplines in the “idle” and “peak” modes, including the target distribution of aircraft between several new applications using the minimax criterion.

5. Conclusions

Based on the conducted research, the following conclusions were obtained:

The problem of parametric optimization in the selection of the number of aircraft based on the multiplicative form of a single efficiency criterion is posed.

When choosing the dispatching algorithm, an approach is proposed based on a combination of sequentially performed ranking operations according to the minimax criterion to ensure the lowest operating costs under the worst conditions for the service delay time.

The results of calculations of the total idle time of the aircraft and the total waiting time of the application, depending on the selected dispatch criteria and the number of aircraft, presented in the paper, confirm the advantages of the developed approach to solving the problem.

Acknowledgments

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