Parameter optimization of the not fully accessible system of the hub airport service based on a simulation model with a fuzzy regulator

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Abstract. The problem of determining the optimal number of technological resources of the hub airport functional subsystem, serving passengers in a separate technological operation, is considered. The analysis is limited to incomplete systems in which the maintenance of certain applications can be performed only by certain resources. As an optimization tool, a simulation model was used that takes into account the features of passenger flows and the hub airport production process and includes a fuzzy controller (FC), which reflects the logic of the airport dispatcher controlling the ground handling process. The paper describes a model example of solving an optimization problem indicating the possibility and feasibility of using a fuzzy controller as a model for the strategy of a human operator. The main result of optimization is the time dependence of the number of technological resources of the functional subsystem which is applicable at the stages of making decisions on increasing its capacity, operational resource management, planning staff shift work, solving a number of other tasks, especially relevant for hub airports with intense but uneven flows of aircraft and passengers.

1. Introduction

The aim of the research is a component of the ground transportation service system at the hub airport - its production unit, designed to perform a specific technological operation and equipped for this purpose with appropriate technological resources. The problem particularly relevant for hub airports, with intense and experiencing sharp fluctuations in the flow of aircraft and passengers and strict requirements for the level of their ground handling, is the determination of the optimal subsystems in terms of the efficiency of the number of resources, which makes it possible to make timely decisions about their capacity. Along with the determination of the maximum number of resources required at the moments of peak load of the subsystem, it is highly desirable to build a time dependence of the required number of resources over large periods of time, the use of which allows airports to increase their efficiency.

The considered subsystems are examples of a control system (CS), in which a group of similar technological resources acts as a control object (CO), and the functions of a control device (CD) are performed by a human operator (airport dispatcher). The range of subsystems under study is limited to incomplete servicing systems, such as, for example, the pre-flight passenger check-in subsystem according to the flight schedule with the allocation of one or several specific check-in counters for serving a certain flight. The characteristics of the airports of the category under consideration [1, 2, 3]
make the simulation computer model the most preferred tool for solving the above optimization problem.

The simulation model of the considered CU includes the model of the CD that reproduces the actions of a person. To formalize the heuristic control rules used by the operator, fuzzy logic methods are used. In the model under consideration, the fuzzy logic controller is a model of the operator’s strategy and thus serves as a model of the CD. Nowadays, despite the large number of publications related to the fuzzy management of a wide variety of objects, an overview of which can be found, for example, in [4, 5], there are practically no works where the issues of fuzzy control of systems and processes of airport ground services are considered. The exception is the work [6], in which the authors raised the topic developed in this paper.

2. Model of the subsystem ground handling services

To form a subsystem simulation model of the initial registration of passengers, a number of assumptions that do not contradict the practice are introduced. Due to the known cyclicity of the schedule of hub airports [7], which makes it possible to describe aircraft flows with periodic functions of time with a period value $T$ equal to days, the simulation experiment reduces to a single model run covering a number of model days. The flow of departing airplanes is assumed to be Poisson with the intensity $\lambda(t)$, varying in time during the model day as shown in figure 1, constructed as a result of processing the schedule of one of the European regional hub airports.

![Figure 1. The intensity of the aircraft flow departing and arriving at the initial passenger terminal.](image)

The variety of aircraft types, passengers of which enter the subsystem for servicing, can be divided into three categories. The numbers of the initial aircraft passengers are taken as discrete random variables evenly distributed within the following limits, depending on the category of aircraft: I category - $5 \div 45$ pass., II category - $35 \div 110$ pass., III category - $90 \div 190$ pass. The shares of the I and III category aircraft, which for most of the model days constitute 20% of the total flow of departing aircraft, do not remain unchanged. According to the current practice, the share of small aircraft rises at the initial stage of the “waves” of mass departures (in figure 1, they include intervals from 10.30 to 13.30 and from 17.30 to 20.00). At the final stage aircraft of higher categories prevail.

Model flow of passengers entering the registration is formed on the basis of the model flow of the departing aircraft.

We use the random value of the time interval $\tau$ (min.) between the time of passenger arrival to the air terminal to pass the pre-flight formalities and departure of the considered flight, with a probability density $f(\tau)$ determined by the three-parameter gamma distribution [1]:

$$f(\tau) = \frac{1}{\Gamma(\alpha)} (\tau - c)^{\alpha-1} \beta^{-\alpha} e^{-(\tau-c)/\beta}, \quad \tau > 0,$$

where $\alpha, \beta, c$ are distribution parameters, $\alpha = 6.1$, $\beta = 12.6$, $c = 20.0$. 
The group nature of the passenger flow is taken into account. The group refers to passengers who jointly show tickets for check-in and have shared baggage. A random number of passengers in a group is modelled using the Poisson distribution. The average size of the group is assumed to be 1.35 pass. The time dependence obtained with allowance for the assumptions of the total intensity $\lambda(t)$ of the passenger flow on all flights for check-in for model days is shown in figure 1.

The registration duration of a group of passengers (min.) is taken as a random variable distributed according to the gamma law (1). The analysis of statistics obtained at a number of airports allowed us to consider the distribution of group registration time depending only on the number of checked baggage items belonging to a group $L$. The distribution parameter $\alpha$ (1) is assumed constant, and the other two parameters linearly dependent on $L$:

$$\alpha = 1.55, \quad \beta = 0.1 \cdot L + 0.38, \quad c = 0.1 \cdot (L + 1).$$

The value of $L$ is assumed to be distributed according to the Poisson law with an average of 0.5.

The planned duration of check-in for all passengers of one plane depends on its category and is assumed to be 90, 115 and 130 minutes for the airplanes of the I, II and III categories, respectively. The planned time from the end of check-in until departure according to a schedule is assumed to be the same for airplanes of all categories, equal to 40 minutes. Service for latecomers, that is, arrivals to the check-in area after the scheduled time of its completion, is not taken into account.

3. **Fuzzy control in the model of ground transportation service subsystem**

To simulate the logic of managing the registration of the initial passengers, a number of assumptions are introduced. It is assumed that the operator’s task is to determine the number $Z$ of workplaces allocated for the registration of passengers departing with the next ($i$-th) aircraft. Practice shows that the most significant factors influencing the decision of the operator, taking into account the start of registration, should be considered as follows: 1) the number $N_i$ of original passengers of the $i$-th aircraft, 2) the number $L_i$ of baggage places of the initial passengers of the $i$-th aircraft, checked out for transportation under the carrier responsibility, 3) the total number of check-in places occupied by passenger services at the time of the decision. For the operator, the source of $N_i$, $Z^L_i$, $L_i$ values, is the dispatch control system and direct observation of the passenger flow.

In addition to the above, the operator takes into account a number of minor factors that are difficult to formalize, the presence of which makes the fact of choosing a certain decision random. To take into account the stochasticity of choice, the probabilities of allocating one, two, and three places for registering passengers of the $i$-th plane $- p_{i1}$, $p_{i2}$, and $p_{i3}$, are introduced, and, accordingly, used by a simulation algorithm to “play” a random number of $Z$ places.

The functions of the FC are reduced to the determination of probabilities $p_{i1}$, $p_{i2}$, and $p_{i3}$ by given values $N_i$, $L_i$ and $Z^L_i$. In the model, FC is implemented according to the standard scheme [8]. It includes the following elements: given membership functions of the input and output variables; a fuzzy base of rules establishing the relationship between inputs and outputs; fuzzy inference mechanism; the method of bringing to the definition of output variables (defuzzification).

We will distinguish the measured input variables $N_i$, $L_i$ and $Z^L_i$, taking values from the set of non-negative integers, and the corresponding linguistic variables $N^*_i$, $L_i$ and $Z^L_i$, taking fuzzy values from the term sets $\{\bar{N}^*_i, \bar{N}^L_i, \bar{N}^M_i\}$, $\{\bar{L}^*_i, \bar{L}^L_i\}$ and $\{\bar{Z}^L_i, \bar{Z}^M_i, \bar{Z}^L_i\}$, respectively. To designate the terms of linguistic variables, we use indices that have the following meaning: $B$ - “large number”, $M$ - “medium number”, $L$ - “small number”. Similarly, the output variables $p_{i1}$, $p_{i2}$, and $p_{i3}$, which accept numerical values on the interval of $[0,1]$, will be assigned the output linguistic variables $\bar{p}^*_i$, $\bar{p}^L_i$, $\bar{p}^M_i$, with the values from the term sets of $\{\bar{p}^B_i, \bar{p}^M_i, \bar{p}^L_i\}$, $\{\bar{p}^B_i, \bar{p}^L_i, \bar{p}^M_i\}$, $\{\bar{p}^B_i, \bar{p}^M_i, \bar{p}^L_i\}$. Graphs of the membership functions of the terms of the input linguistic variables, obtained using the results of processing statistical
data of the production information system of one of the major regional airports and interviewing specialists of its respective services, are shown in figure 2.

![Figure 2. Membership functions of terms of input linguistic translations.](image)

The fuzzy rule base for input linguistic variables $N_i^l, L_i^l, Z_i^z$ and output - $p_{i1}^l, p_{i2}^l, p_{i3}^l$ is presented in the form of table 1, where the columns correspond to individual fuzzy logical rules.

| $N_i^l$ | B | B | B | B | B | M | M | M | M | M | M | L | L | L | L | L | L | L |
|--------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $L_i^l$ | B | B | B | L | L | L | B | B | B | L | L | L | B | B | B | L | L | L |
| $Z_i^z$ | L | M | B | L | M | B | L | M | B | L | M | B | L | M | B | L | M | B |
| $p_{i1}^l$ | L | M | M | L | M | M | L | M | M | M | B | B | B | B | B | B |
| $p_{i2}^l$ | M | B | B | B | M | M | B | B | B | M | M | L | L | L | L | L | L | L |
| $p_{i3}^l$ | B | B | M | M | M | L | B | M | L | M | L | L | L | L | L | L | L | L |

A small number of terms of linguistic variables makes it possible to dispense with the base of rules of small volume. In order to further simplify the fuzzy control procedure, we will consider the terms of output linguistic variables to be singleton (one-point) fuzzy sets, giving them the values:

$$p_{i1}^l = p_{i2}^l = p_{i3}^l = 0,$$
$$p_{i2}^m = p_{i3}^m = 0.5,$$
$$p_{i1}^b = p_{i2}^b = p_{i3}^b = 1.$$

For each of the three output variables, a fuzzy inference algorithm is implemented separately using the singleton rule base [9], which can be considered as a special case of the Mamdani algorithm [10]. The results are fuzzy probabilities $\tilde{p}_{i1}, \tilde{p}_{i2}, \tilde{p}_{i3}$, having, due to the singleton nature of the terms of the output linguistic variables, discrete membership functions. The defuzzification of the quantities $\tilde{p}_{i1}, \tilde{p}_{i2}, \tilde{p}_{i3}$, performed by the centroid method [8], provides the desired probabilities $p_{i1}, p_{i2}, p_{i3}$.

4. Setting the optimization problem and the approach to its solution.

In the time interval $[0,T]$ it is required to determine the time dependence of the optimal number $z_{opt}(t)$ of resources of the same type in an incompletely accessible service system with the characteristics described in part 2, using fuzzy control considered in part 3. Optimal means the minimum number of check-in sites sufficient for the airport to start timely performing this operation with a given $P$ reliability, provided that the check-in of passengers to the $i$-th aircraft begins only if there are $Z_i$ free places determined by a dispatcher.

To solve the optimization problem, we use the approach, which allows to approximately determine $z_{opt}(t)$ by means of the results of a single run of the simulation model, the duration of which is set on the basis of the required accuracy. It is assumed that the model number $z_{max}$ of airport resources is so high that it obviously exceeds the value of the desired optimal number $z_{opt}(t)$ for any moment $t \in [0,T)$ of the model day. Due to the stochasticity of the optimized subsystem processes, the total number $Z(t)$ of check-in places occupied in servicing passengers at the time $t \in [0,T)$ is a random process with a
distribution function \( F_Z(z,t) = P[Z(t) \leq z], \) \( 0 \leq z \leq z_{\text{max}}, \) determined using simulation modelling. According to the results of the simulation model run, the desired optimal number \( z_{\text{opt}}(t) \) needed to service the passengers of all aircraft at the time \( t \in [0,T] \) is determined as the minimum of the values \( 0 \leq z \leq z_{\text{max}}, \) that ensure the fulfilment of the condition \( P[Z(t) \leq z] \geq P. \)

5. Results of a model example of an optimization problem solution

The formulated optimization problem was solved using a simulation model programmatically implemented on the basis of AnyLogic 6 University simulation system. For the above source data, when using modern personal computing, the cost of computer time for a solution with an error of the obtained results within 1% did not exceed 15 minutes.

Some of the optimization results are presented in figure 3. The main result was the time dependence of the optimal number of resources \( z_{\text{opt}}(t) \) at the level of reliability \( P = 0.95. \) The maximum number of resources per day was 58 units, but the number close to this level is required for only about 2 hours. The uneven flows inherent in the hub airport lead to the fact that a much more modest number of places, not exceeding 28 units, is sufficient for 20 hours. Shown in figure 3 time dependence of the average number \( \bar{Z}(t) \) of registration sites occupied by the service makes it possible to present the degree of variation of a random process \( Z(t). \)

The average waiting time \( \bar{T}_w(t) \) in the queue for the registration of passengers arriving at the terminal at the moment \( t \in [0,T] \) allows us to assess the level of passenger service quality. For long periods of time, this value remains at a fairly high level, reaching 7.5 minutes. Such values do not indicate a high comfort of passengers' stay at the airport and serve as a basis for revising the approach to managing the check-in process, or for a more radical step in moving the airport to more productive passenger check-in schemes.

The results include the time dependence of \( N_{0.99}^{0.99}(t), t \in [0,T] \) 0.99-quantile the number of passengers in the queue and the service in the check-in area. According to the data presented in figure 3, the required capacity of the airport check-in area with a reliability of 0.99 is about 400 passengers.

6. Conclusion

Simulation modelling allows us to create a detailed stochastic portrait of functional subsystems of airports, including those related to such a promising category as hub airports. Using FC to simulate the behaviour of a dispatcher who controls airport processes makes it possible to increase the adequacy and accuracy of simulation models. Optimization of the parameters of functional subsystems may allow airport services to provide rational solutions for such tasks as operational resource manoeuvring, redistribution of forces and resources between subsystems, planning staff shift work, calculating the required number of shifts, and other tasks urgently important for hub airports.
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