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DETERMINATION OF AIR TRANSPORT SECURITY FACTORS VULNERABLE TO ACTS OF UNLAWFUL INTERFERENCE

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The object of research is air transport security system. The prerequisites for implementing security measures in air transport have been investigated. This is due to the fact that the most serious threat to the safety of air transport is unlawful interference acts (UIA), the commission of which is a crime and cannot be justified. Therefore, it is constantly necessary to promote the increase of efficiency in combating this evil at the global level.

Factors influencing the safety of the ATS components depending on the features of their functioning have been determined. For the "air transportation" ATS component the most vulnerable object is the airport, where the processes of the initial and final stages of the flight take place. For the "special purpose aviation" component of the ATS, the most vulnerable sector is aviation-chemical work in the agricultural sector. In this sector, aviation protects grain crops with chemicals. It has been found that pesticides can be a significant threat due to their use for the purpose of biochemical terrorism.

A mathematical model has been developed and implemented that reflects the dynamics of passenger flow through airport procedures. The dynamic distribution of airport resources for performing screening procedures both during normal operation and when operating under threat conditions was calculated. As a result, extreme cases of resource requirements were identified – for performing security checks lasting an average of 7 minutes per passenger. When the throughput is exceeded by 2 times, the need for the corresponding resources is 4.7 times greater than for performing security checks lasting an average of 3 minutes per passenger and with minimally sufficient process throughput to complete everything within the established time frame

Keywords: airport security, unlawful interference acts, safety factors of aviation-chemical works, types of biochemical terrorism, airport screening procedures, airport resources, mathematical modeling

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1. Introduction

Air transport is a particularly vulnerable mode of transport in relation to the implementation of unlawful interference acts (UIA), therefore an important role in ensuring the safety of civil aviation is to protect infrastructure. The most vulnerable of these facilities is the airport, so the airport management needs to constantly improve the level of aviation security and assess the impact of security measures on the average time of the passenger's stay at the airport.

Activation of the activity of agricultural producers in modern conditions of precision farming, especially in the field of crop production, leads to the need for wider use of air transport in the processing of crops and some technological operations in the process of growing crops. But the important role of small aircraft has a downside. The problem is the possibility of using aviation in deliberate and non-intentional acts of terrorism, especially during military operations in Ukraine.

Therefore, studies on the development of measures to ensure the safety of civil aviation are relevant.

2. Literature review and problem statement

The problem of assessing the level of aviation safety and finding new approaches to the analysis of the state of aviation safety is reflected in the work [1] using fractal and statistical tools. A multi-factor hierarchical model of describing the level of safety of air transport has been developed on the basis of applying a systematic approach in the context of sustainable development, combining economic, technological, social and environmental components. Such a systematic approach does not take into account the peculiarities of the functioning of the components of the aviation transport system (ATS).

In the paper [2], theoretical approaches to the measurement of safety levels using the sequence coefficient test are proposed. Particular attention is paid to the threats and risks of civil aviation in the context of globalization processes. The work focuses on the search for methods for assessing the "safety space" of civil aviation. From a practical point of view, this can cause difficulties associated with determining the threat when serving passengers at airports.

The complex concept of "civil aviation safety" and its components was studied in the work [3] on the basis of scientific analysis of the current legislation, international law and scientific literature, a meaningful author's definition was proposed. Thus, the proposed basic aspects define the concept of "aviation security" in two keys: as the state of protection of aviation from illegal interference in the activities of the aviation industry, or as a set of measures for aviation security. But the work excludes the mandatory component, which consists of human and material resources intended to protect civil aviation from UIA.

The author of the work [4] states the need for the smooth functioning of complex systems, which requires the improvement of decision-making methods for rapid response and resumption of activities in unstable conditions of system management. But rapid response does not solve the problem of the formation of security measures depending on the level of threat. This problem is partly reflected in the initiative of the International Civil Aviation Organization (ICAO) in the field of security and is formulated as "the development of an effective response to violations of the aviation system created by natural disasters, conflicts or other causes" [5].

Assessment of aviation security by scientists is carried out by approaches from different angles. The paper [6] considers aviation security and its threats as a component of the air transport system, as well as risk management associated with "vulnerability". The paper considers the quantitative display of the protection object state from the point of view of aviation security and calls it a "vulnerability", which indicates the protection degree of transport infrastructure objects. But in the work, it is not noted that the airport is a critical object of air transport infrastructure, where the beginning and completion of air transportation takes place. Therefore, there is a problem of a more detailed study of the duration of procedures for passengers to pass the stages of inspections at the airport.

The opinion of the authors [7] in view of the situation with the dynamics of integral indices and parameters of the components of UIA demonstrates a general rapid decline in institutional and managerial capacity. Methods of aviation transport safety integration in the mechanism of interaction of sustainable development goals with strategic management of sustainable development security through managerial, functional and information links with subsystems of sustainable development and security of different hierarchical levels are disclosed. The place and role of aviation safety in ensuring fundamental national interests – sustainable development of the national economy. It is revealed that safety of air transport primarily depends on the social component, economic and technological development of air transport. However, it should be noted that in this work there are difficulties associated with determining the factors of influence on the aviation safety of such components of ATS as "air transportation" and "special aviation".

In work [8], the scientific and practical bases of passengers and clientele quality of service at the airport are researched. A methodology for assessing the quality of airport services has been developed, which reveals the essence of aviation security in the airport quality management system. A sequence of the aviation security system evaluation is proposed, reflecting the cost approach, the use of which involves the definition of financial reserves to ensure aviation security in the continuous implementation of the quality management system. The quality of passenger service at the airport is affected by the length of time for the passage of security procedures, which increases when an UIA threat arises. Therefore, it is necessary to take into account the use of existing and additional resources related to the level of threat.

The paper [9] analyzes the impact of perceived waiting time on the activities of the airport aviation security service, applying psychological and emotional reactions of passengers. Structural equations were also modeled and the perceived waiting time was determined as a subfactor of psychological reactions of passengers. The results of this study can be used as basic data for modeling the dynamics of the passengers' flow movement through the procedures at the airport. Analysis of various airport security systems is done in the work [10], recommendations were developed for the airport administration regarding the optimal use of resources at checkpoints. But the reasons for the queues have only been revealed at airport security lanes. Given the significant number of procedures for checking passengers at the airport, it is necessary to take into account the total time passengers stay at the airport before boarding the plane.

Russia's invasion of Ukraine on February 24, 2022 led to the closure of air traffic in Ukrainian airspace. The consequences of this phenomenon are highlighted in [11], which consist in the need for airlines to use workarounds and look for alternative routes. All this leads to a significant increase in flight time on routes. This study also provides a forecast of global aviation CO_2 emissions for the next five years under two different scenarios for the development of a military conflict in Ukraine, built using the SARIMA model. Forecasting scenarios for the development of a military conflict on the territory of Ukraine does not take into account such an important component of ATS as the performance of aviation-chemical work when growing crops. At the same time, it is necessary to take into account the factors of the impact of aviation-chemical work when growing crops on the environmental component of aviation safety.

Attention should be paid to the multiple regression model of airport aviation security developed in the work [12]. The model demonstrates the importance of the crime factors and economic factors influence. The obtained results confirmed the assumptions about the dependence of illegal interference acts and crime of the territory in which the airport is located: there is a reliable positive correlation; with an increase in crime, there is a +0.017 increase in acts of unlawful interference. From a practical point of view, the developed model of aviation security allows to manage and predict the level of danger in order to ensure the safety of the airport. Potentially, the model can be expanded by creating a multi-level model of aviation security, which requires further research, taking into account the aviation security factors of the PBX components.

Critical analysis of sources made it possible to systematize unresolved issues regarding the improvement of the process of formation of aviation security, which are as follows: the prerequisites and the definition of factors of influence on the ATS components have not been studied; the effect of time duration on security procedures depending on the threat level was not investigated. Therefore, it is necessary to take into account additional significant factors: appropriate countermeasures for each type and level of threat, including the activities of personnel and a set of appropriate technical means of protecting the object, reflecting available and additional resources.

3. The aim and objectives of the study

The aim of the study is to determine the aviation security factors of critical objects of aviation transport infrastructure that have vulnerabilities in relation to the implementation of UIA and other unpredictable dangerous events. The development and implementation of a mathematical model that reflects the dynamics of the flow of passengers through procedures at the airport will allow to explore how increasing the average time of checking one passenger for safety affects the time spent by one passenger in queues and directly in the processes of these checks, subject to limited resources for such checks.

To achieve this aim, the following objectives are solved:

– identify the prerequisites for the implementation of safety measures in the performance of air transportation and in the performance of aviation-chemical works (ACW);

– develop and implement a mathematical model that reflects the dynamics of the flow of passengers during the passage of mandatory procedures at the airport both during normal work and when working under threat conditions.

4. Materials and methods

The object of the study is the safety system in aviation transport.

The basis for the construction of ways to solve the problem is the hypothesis of the dependence of the speed of passage of passengers checks at the airport on the distribution of existing resources and the attraction of additional resources.

For simulation purposes, it was assumed that the arrival of passengers of one flight at the airport is random, and the arrival rate has an approximately normal distribution. Then the number of passengers of one flight already at the airport is described by the corresponding probability distribution function. Let's also assume that some passengers arrive in advance.

During the study, the following simplifications were adopted: since passenger flows are variable in time, for the purpose of modeling, changes are considered with a discrete step of the order of minutes on the total time interval measured in weeks.

To objectively assess the factors that affect the safety of the operation of air transport, a systematic approach should be applied, since the air transport system consists of a subsystem of elements and connections (Fig. 1), which have their own peculiarities of functioning.

The use of analysis and synthesis methods made it possible to determine the key conceptual provisions of research work on the organization of aviation security. An analytical study to identify the causes and factors of the implementation of acts of illegal intervention allows to develop measures (countermeasures) to prevent dangerous events in the future.

Methods that ensure the safety of aircraft performing aviation-chemical work consist in the presence of parking in a closed hangar. Also, the hangar must be equipped with an anti-theft lock and have means of preventing unauthorized flight.

Safety methods for storing pesticides and fertilizers are to prohibit access to them by unauthorized persons. Safe storage includes a list of reservations regarding the storage of pesticides: various reliable door locks, electronic security system, incoming and outgoing blocking of access to the storage place. Buildings that store pesticides and fertilizers must have a solid structure to prevent unauthorized intrusion.

Mathematical modeling methods made it possible to develop a model for the formation of an aviation security system at the airport, which reflects the dynamics of passenger movement at the airport. This made it possible to calculate the dynamic distribution of airport resources to perform inspection procedures both during normal operation and when working under threat conditions. In this case, the criterion is to minimize the greatest time spent by passengers on checks and expectations.

5. Results of safety system development in aviation transport

5. 1. Prerequisites for the implementation of security measures in aviation transport

It should be noted that terrorism is the most serious threat to the security of the international world, the terrorist acts of which are a crime and cannot be justified, therefore, it is constantly necessary to promote efficiency in combating this evil at the global level. The classification of terrorism is divided into the following categories [13]:

1. Ideological component and sphere of manifestation of terrorism: political; state; religious; nationalist; selfish; criminal.

2. The scale of terrorism; domestic, international.

3. Types of terrorism: ordinary; nuclear; biochemical; economic; electromagnetic; cybernetic; informational.

Aviation transport is the basis of the system of formation of aviation security measures for the components of the aviation transport system, which consists of two subsystems: air transportation and special forces aviation.

To clarify the factors that affect the safety of operation of air transport, it is necessary to consider the elements and connections in the aviation transport system [14]. To ensure safety measures of the aviation transport system (ATS), it is necessary to determine the factors of influence on the safety of its components, depending on the features of operation.

As for the ATS component of air transportation, the most vulnerable object is the airport where the start and end of the flight takes place. The network of airports provides security, regularity of flights, ground maintenance of air transportation at their initial and final stages.

UIA statistics for the period from 2000 to 2023 in the terminals of airports in the world is given in Table 1 [15, 16].

Thus, airports should be classified as critical infrastructure that requires the greatest protection against illegal interference. Statistical world information on the UIA implementation in airport terminals is the basis for the development of future security measures [15, 16]. Conducting an analytical study to identify the causes and factors of the implementation of UIA allows to develop measures (countermeasures) to prevent dangerous events in the future.

Analysis of the above statistics indicates that in most cases the cause of UIA in airport terminals is the detection of a bomb. It should also be noted that the largest number of wounded falls on 2016, and the largest number of deaths due to UIA falls on 2021.

As for the special-purpose ATS component, aviation security factors are formed depending on the specific functional features of the sectors of this component. The most vulnerable sector of special-purpose aviation is aviation-chemical work in the agricultural sector. In this sector, air transport participates in the technological process of growing crops. At the sowing stage, aviation work is performed by introducing seed material. During the growing season, by air transport, agrochemicals are introduced, pest, disease and weed control, resettlement of biological objects, desiccation, defoliation [17].

When implementing the protection of the base of agricultural aviation, two important factors have an impact, which include the safety of storage of aircraft and the safe storage of pesticides and fertilizers.

Methods to ensure the safety of aircraft, is the availability of parking in a closed hangar. Also, the hangar has both equipped with anti-theft lock and have means of preventing unauthorized flight.

Table 1

Dynamics of unlawful interference acts (UIA) in the terminals of airports of the world for 2000–2023

No.	Year	Country/UIA at the airport terminal	Number of victims	
			Dead	Wounded
1	2000	Philippines/Bomb	0	0
2	2001	Pakistan/Bomb	0	0
3	2001	Thailand/Bomb	0	0
4	2001	South Africa/Bomb	1	0
5	2002	Afghanistan/Bomb	5	0
6	2002	Pakistan/Bomb	0	0
7	2003	France/Bomb	0	0
8	2003	Philippines/Bomb	21	150
9	2006	Pakistan/Bomb	0	30
10	2007	Afghanistan/Bomb	2	4
11	2007	Scotland/Bomb	1	3
12	2007	Pakistan/Bomb	0	5
13	2007	Spain/Bomb	0	0
14	2009	Somalia/Bomb	21	40
15	2009	Afghanistan/Bomb	3	6
16	2010	Philippines/Bomb	1	8
17	2010	Somalia/Bomb	8	0
18	2011	Russia/Bomb	31	130
19	2012	Bulgaria/Bomb	31	130
20	2016	Belgium/Bomb	34	230
21	2016	Turkey/Bomb	41	239
22	2017	France/Bomb	0	0
23	2018	Afghanistan/Bomb	10	0
24	2019	Saudi Arabia/Bomb	1	42
25	2020	Yemen Bombing a/p	28	107
26	2021	Colombia/Bomb (suicide bomber)	2	0
27	2021	Afghanistan/Bomb (suicide bomber)	183	150
28	2022	UAE Drones	3	6
29	2022	Somalia Simultaneous attacks a/p	60	108
30	2023	Afghanistan/Bomb	20	30
In just 23 years			472	1418

Safety methods for the storage of pesticides and fertilizers is to prohibit access to them by unauthorized persons. Safe storage includes a list of reservations regarding the storage of pesticides: various reliable door locks, electronic security system, incoming and outgoing blocking of access to the storage place. Buildings that store pesticides and fertilizers must have a solid structure to prevent unauthorized intrusion.

The last example of UIA in the agricultural sector in Ukraine took place in 2022–2023 after the shelling of agricultural land and grain warehouses by Russian troops, which led to the destruction of agricultural products and the obstruction of harvesting.

Also there is a problem of protection of grain crops by chemical means, the processing of which is carried out by air transport. Pesticides can be a significant threat due to their use for terrorism and biochemical terrorism. The types of biochemical terrorism and their spheres of influence are shown in Fig. 1.

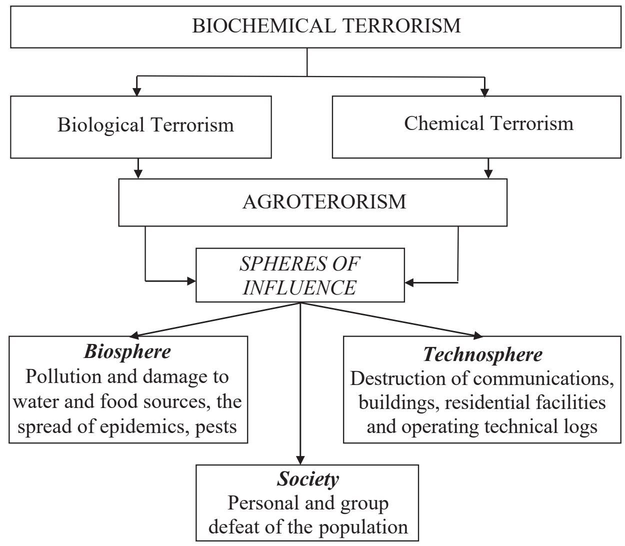

Fig. 1. Types of biochemical terrorism and their spheres of influence

Consequently, the field of aviation security requires the necessary implementation of constant supervision, analysis, improvement and use of effective modern technical means and human resources.

Constant supervision is carried out by the aviation security service, which is a special unit and performs the function of protecting aviation entities from illegal actions on their safe and normal activities [18].

The safety system of airport includes control-security systems that are combined with each other and have development in the integration direction.

The purpose of this type of control is to prevent terrorist acts and hostage-taking on board the aircraft, as well as to prevent the illegal export of prohibited items and substances. In a special control zone, there is a preliminary inspection of passengers and hand luggage immediately before boarding the plane [19].

The constant development of the global market for all types of air transportation and other types of aviation work enhances competitiveness in the transport industry, so the topic of aviation security is a priority in solving the issue of safe activities of civil aviation.

5. 2. Development and implementation of a mathematical model for the formation of an aviation transport safety system

Taking into account the research and determination of factors of influence on aviation safety of ATS components, there is a need for different approaches to develop safety measures in accordance with the peculiarities of their functioning. This makes it impossible to cover the entire PBX security system within one model. Therefore, in this study, it is proposed to develop a mathematical model of passengers passing inspection procedures at the airport both during normal work and when working under threat conditions. This model will precede the development of the model of aviation security subsystem "Special forces aviation".

The airport is the main infrastructure facility where various streams are processed, namely: passenger, postal and cargo, aircraft, flight crews, etc.

These flows change over time. Changes are usually considered in discrete steps. Depending on the task, the step can be taken in the size of several minutes (5, 10, 15, 20, 30), hours, days, weeks, months. For simulation, steps in minutes over a total time interval measured in weeks will be considered. Due to the fact that in the materials of IATA [20] in the calculated formulas of the required amount of equipment, areas, specialists, steps of 10, 15, 20 minutes are used. The main and largest flow at the airport is the flow of passengers, constantly changing both during the day and during the week, month, year. Changes depend on the schedule, number of flights, types of aircraft used, season and demand for air transportation.

Assessment of the impact of security measures on the average time of the passenger's stay at the airport and on the time spent by it on the procedures of registration of departure (registration, passport, customs and security control) is considered according to the conditional time schedule of the stay of one passenger at the airport and the passage of the processes of preparation for departure (Fig. 2).

The time intervals presented in the diagram are not specified, since they are not the same for both passengers and airports. Each airport in the organization of work with passengers has its own characteristics and differences. To assess the quality of service, the total time spent by the passenger on registration, passport, customs and security control, including the time spent waiting in queues, is important. Also important is the availability and quality of services that passengers can use in their free time.

The time period of the passenger's stay at the airport is conditionally divided into six parts. These include: Δt_r – the time spent on check-in and baggage; Δt_p – the time spent on passport, customs and security control; Δt_d – the time of control before boarding the plane, landing and waiting for departure; Δt_{v1}, Δt_{v2}, Δt_{v3} – free time that the passenger has during the passage of these procedures.

Passenger check-in is usually 2 hours before departure and ends 40 minutes before departure. But passengers of one flight may not arrive at the airport at the same time. Thus, it is accepted that the arrival of passengers of one flight is random, and the arrival speed has an approximately normal distribution.

In accordance with the procedural scheme shown in Fig. 2, let's divide the flow of passengers $F(t)$ into those who have queued for check-in and baggage drop-off, but have not yet passed $F_r(t)$; who has queued for security, customs and passport control, but has not yet passed $F_p(t)$: who has queued to board the plane, but the plane has not yet departed $F_d(t)$ and passengers waiting for the start of the next procedure, use additional services at the airport $F(t)_{v1}$, $F(t)_{v2}$, $F(t)_{v3}$.

These streams are represented by the following equation:

$$F(t)=F_r(t)+F_p(t)+F_d(t)+ \\ +F(t)_{v1}+F(t)_{v2}+F(t)_{v3}. \quad (1)$$

Visual passage of all procedures by passengers of one flight is shown in Fig. 3. Lines reflecting the passage of procedures by passengers are listed on the left to the right. The horizontal section shows the distribution of time at the airport for passengers of a particular percentage. The vertical section shows the distribution of the number of passengers who have already arrived at the airport between the entered functions $F(t)_{v1}$, $F_r(t)$, $F(t)_{v2}$, $F_p(t)$, $F(t)_{v3}$, $F_d(t)$.

Fig. 3 shows that the average time that a passenger spends before queuing for check-in (baggage change) is 24 minutes, the average time that a passenger spends until the end of check-in is 10.6 minutes. The average time before the passenger gets in line for checks is 30.4 minutes, the average time before the end of checks is 11.3 minutes. The average time to landing is 23.7 minutes, the average time from the beginning of landing to departure is 9.5 minutes, in general, the average time a passenger stays at the airport is about 110 minutes.

The change in the speed of the procedures affects both the distribution of the number of passengers between the functions $F(t)_{v1}$, $F_r(t)$, $F(t)_{v2}$, $F_p(t)$, $F(t)_{v3}$, $F_d(t)$, and the distribution of the total time of the passenger's stay at the airport.

The assessment of the quality of service at the airport is more influenced by the three average time intervals introduced above:

– the moment when the passenger queued for check-in (baggage change), before the end of check-in;

– the moment when the passenger queued for control and checks, until the end of these checks;

– the moment when the passenger stood in the queue for landing and before departure.

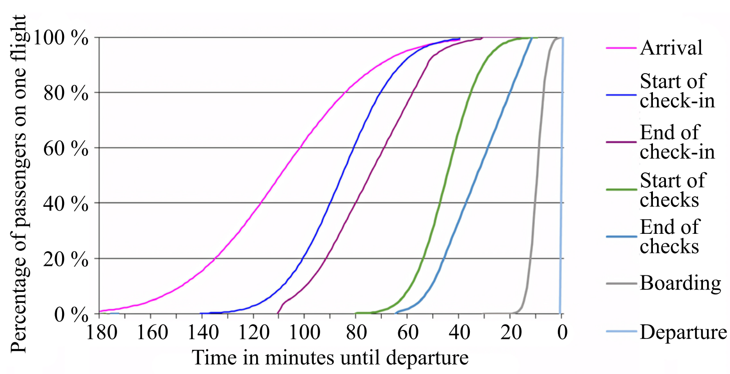

Fig. 3. Passage of all procedures by passengers of one flight before departure

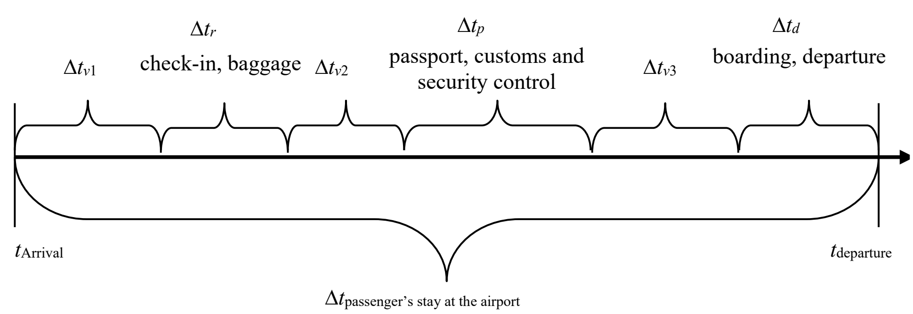

Fig. 2. Conditional time schedule of the passenger's stay at the airport

Also important is the total time that the passenger spent at the airport.

The following is a description of the notation system and relationships that will be used in the model. To describe the safety components, it is possible to use the definitions given in p. V. "Methods for assessing the level of threat and risks" of the Order [20–22]:

– Z – a set of potential threats that can be identified;

– S_ζ – multiple possible scenarios for each threat, $\zeta \in Z$. Formally, it will be considered that sets S_{ζ_1} and S_{ζ_2} for different threat $\zeta_1 \neq \zeta_2$ do not intersect, i.e. $S_{\zeta_1} \cap S_{\zeta_2} = \varnothing$;

– $\Theta = \bigcup_{\zeta \in Z} S_\zeta$ – combining all scenarios of all threats. Since the sets of scenarios do not intersect, each scenario uniquely identifies the corresponding threat;

– D_σ – a set of scenarios of protection against a threat for each threat scenario, the $\sigma \in \Theta$ generated by a detailed analysis of the threat scenario (purpose, method of committing an UIA, means of attack, performers).

External factors in relation to the model are the threat and the threat scenario, and the protection scenarios are selected. The threat appears and over time may change or disappear.

As a possible consequence of using a protection scenario for passengers may be:

– additional checks;

– increasing the time of procedures (checks);

– delay or postponement of departure for a considerable time;

– additional measures for different flights may be different.

Thus, multiple flights are considered for a significant period of time $[0, T]$ (weeks, months), in which additional security measures will be applied. Multiple J flights consist of all flights during this period. The $j \in J$ index will determine both the flight time on the schedule and the day of the week (month).

The formulation of a finite-dimensional mathematical model makes the transition from continuous time to individual time intervals. To do this, let's sample the time interval $[0, T]$ in increments Δt the order of one minute. In this case, T will be considered as a set of ordered time slots $t \in T$ the same length of Δt.

Parameters of the mathematical model accept some models of passenger behavior, which will describe the arrival of flight passengers at the airport and their stay in the queue for checks. Time intervals consist of two parts: waiting in the queue and direct passage of the procedure (check). It is the passage of the inspection procedure that depends on the chosen security measures – the stricter the measures, the longer this period of time. Waiting in the queue depends on the behavior of passengers and the capacity of the airport, which also depends on the chosen security measures and the allocated available and additional resources of the airport.

If the relative numbers are multiplied by the expected number of passengers on flight N_j, then it is possible to get the models of passenger behavior for each flight in the absolute number of passengers.

Then each flight j is given a subset of time intervals $T_j \subset T$, which will include time intervals $t \in T$ starting from when the first passenger of the flight arrives at the airport three hours before the scheduled departure according to the adopted behavior model and an interval of 5 hours, which allows for a flight delay of up to 2 hours. The time intervals of 3 and 5 hours are considered model parameters, which can vary depending on the research question and the task at hand.

The following is a description of the process of passengers passing checks formally mathematically in general form.

Let the passengers of flight j have to pass a set of checks, $C_{j\delta}$ which are determined by the threat scenario σ_j and the protection scenario valid at the time of preparation for the flight $\delta \in D_{\sigma_j}$,where D_{σ_j} – the set of protection scenarios that will be applied and that can be selected using the model. Since the checks occur in a certain order, then the set $C_{j\delta}$ is ordered, and each element $c \in Cj_\delta$ has its number $i(c)$ from 1 to $|C_{j\delta}|$. Let's assume that for different $\delta \in D_{\sigma j}$ sets $C_{j\delta}$ do not intersect. Then each element $c \in C_{j\delta}$ clearly corresponds to the protection scenario δ.

The number of passengers on the flight is denoted by j, who can queue for inspection $c \in Cj_\delta$ at time $t \in Tj$ according to their behavior model, as b_{jt}^c. The number of passengers of flight j arriving at the airport is denoted as b_{jt}^0. Parameters b_{jt}^0 for flight j must be related by the equality $\sum_{t \in T_j} b_{jt}^0 = N_j$.

Number of passengers V_{jt}^c flight j at interval t, which have already passed the previous check to $\breve{c}$ and have not yet stood in line to pass the check c, is determined by the ratio:

$$V_{jt}^c = V_{jt-1}^c + a_{jt}^{\breve{c}-} - a_{jt}^{c+}, \tag{2}$$

where $a_{jt}^{\breve{c}-}$ – the number of passengers who have already completed the preliminary check at interval t, a_{jt}^{c+} – the number of passengers who queued for inspection c at interval t.

To check c, which has the number $i(c) = 1$, $a_{jt}^{\breve{c}-} = b_{jt}^0$.

The number of passengers waiting in line for screening is determined by their behavior pattern, but cannot be greater than the number of available passengers:

$$a_{jt}^{c+} = \min\left\{b_{jt}^c;\, V_{jt-1}^c + a_{jt}^{\breve{c}-}\right\}. \tag{3}$$

Number of passengers H_{jt}^c flight j at interval t, which are in the queue for inspection c, is determined by the ratio:

$$H_{jt}^c = \max\left\{0;\, H_{jt-1}^c + a_{jt}^{c+} - p_{jt}^c \Delta t\right\}, \tag{4}$$

where p_{jt}^c – the throughput of the verification stage c for flight j at interval t.

Let the check-in of one passenger c on flight j take an average time $\Delta\tau_j^c$.

Then the number of passengers, who complete the check after time c is $\Delta\tau_j^c$, is defined by the following ratio:

$$a_{j(t+\Delta\tau_j^c)}^{c-} = \min\left\{p_{jt}^c \Delta t;\, H_{jt-1}^c + a_{jt}^{c+}\right\}. \tag{5}$$

After passing the checks normally, all passengers should be allowed to board the plane. In the model, this is expressed by the fact that the total number of passengers who have completed the last check is equal to the number of passengers who arrived at the airport, namely:

$$\sum_{t \in T_j} a_{j(t+\Delta\tau_j^c)}^{c-} = N_j,\; i(c) = |C_{j\delta}|. \tag{6}$$

When conducting inspections, various resources are required. Airport resources are considered to be: areas, various equipment and working time of specialists of various qualifications who are involved in these inspections and procedures. The average number of resources required to check type c of one passenger of flight j is collected in a vector and denoted by $\overline{r}_j^c$. Let certain resources be allocated in the interval t for checking c passengers of flight j, which are represented as a vector $\overline{x}_{jt}^c$. Then the bandwidth p_{jt}^c at interval t is determined by the most "scarce" resource:

$$p_{jt}^{c}=\min_{k\in K_j^c}\left\{\frac{x_{jtk}^{c}}{r_{jk}^{c}\Delta\tau_j^{c}}\right\}, \tag{7}$$

where K_j^c – a set of vector components $\bar{r}_j^c$ and $\bar{x}_{jt}^c$.

The limitations of airport resources are considered. Some airport resources cannot be increased over the total time interval considered in the model [0, T] (for example, area). There are also resources that can be increased by using a reserve, or renting (portable equipment), some can also be increased by redistributing their quantity between intervals t (time of specialists with subsequent reimbursement).

To reflect different types of resource constraints in the model, let's divide the entire set of resource types, K, used at the airport for screening procedures, into three non-overlapping subsets: $K=K^{I}\cup K^{II}\cup K^{III}$.

The first subset of resources K^I has constant constraints and operates on any interval t:

$$\sum_{j\in J_t}\sum_{c\in C_{j\delta}} x_{jtk}^{c}\le X_k,\ k\in K^{I},\ t\in T, \tag{8}$$

where X_k – the number of resource k at the airport, J_t – the number of flights for which checks can be performed in interval t. The sets J_t are obtained as a result of the inverse mapping of the set T into J, namely: $J_t=\{j\in J|t\in T_j\}$.

The second subset of resources K^{II} has a limit on their use, which can be increased for all periods of the set T:

$$\sum_{j\in J_t}\sum_{c\in C_{j\delta}} x_{jtk}^{c}\le X_k+y_k,\ k\in K^{II},\ t\in T, \tag{9}$$

where y_k – an additional resource, the volume of which is set by the model.

The third subset of resources K^{III} has flexible use with a limited quantity at each interval t and a limit on total use:

$$\sum_{j\in J_t}\sum_{c\in C_{j\delta}} x_{jtk}^{c}\le y_{kt},\ k\in K^{III},\ t\in T,$$

$$y_{kt}\le X_k^{1},\ t\in T;\ \sum_{t\in T} y_{kt}\le X_k^{\Sigma},\ k\in K^{III}, \tag{10}$$

where y_{kt} – an additional resource, the volume of which is determined by the model, X_k^1 – limiting the amount of resource in one interval, X_k^{Σ} – total limit on the amount of resource.

A mathematical model can be used to consider different issues and obtain different estimates.

The issue of speed of inspection is considered as one of the criteria for the quality of passenger service. This question can be formulated as follows: what are the threats under the influence of $\zeta\in Z_T$ at the time period T with the expected scenarios of its implementation $\sigma\in\Theta_T$ select protection scenarios $\delta\in D_\sigma$. It is also important to allocate existing airport resources and attract additional resources so that the average time passengers spend going through screening procedures and waiting in lines is minimal within the possible time frame.

To answer the question, it is necessary to calculate the average time $\Delta\tau_\delta^0$ passengers going through security checks and waiting in lines. It is calculated as the total time spent by all passengers divided by the number of all passengers, namely:

$$\Delta\tau_\delta^{0}=\frac{\sum_{j\in J}\sum_{c\in C_{j\delta}}\sum_{t\in T_j} H_{jt}^{c}\Delta t+\sum_{j\in J}\sum_{c\in C_{j\delta}} N_j\Delta\tau_j^{c}}{\sum_{j\in J} N_j}. \tag{11}$$

To reflect the possibility of choosing protection scenarios in the model, let's introduce Boolean variables $z_{\sigma\delta}\in\{0,1\}$, $\delta\in D_\sigma$, $\sigma\in\Theta_T$, which will indicate whether or not the protection scenario δ is selected from the threat scenario σ. Since one of the scenarios must be selected, this requirement is given by the condition $\sum_{\delta\in D_\sigma} z_{\sigma\delta}=1$ for each $\sigma\in\Theta_T$. If during the period T the threat disappears, then the standard conditions are formally considered as some threat σ_0 requiring standard security measures $\delta\in D_{\sigma 0}$.

In this case, both standard and enhanced security measures are described equally within the same model.

In conclusion, the mathematical model can be presented as a system of relations, in standard form, by simplifying and clarifying some previous expressions.

Minimize the total time spent by passengers on checks and waiting for checks in the queue for T period:

$$\sum_{j\in J}\sum_{\delta\in D_{\sigma_j}}\sum_{c\in C_{j\delta}}\left(N_j\Delta\tau_j^{c} z_{\sigma_j\delta}+\Delta t\sum_{t\in T_j} H_{jt}^{c}\right)\to\min, T, \tag{12}$$

with restrictions:

– block constraints valid for $j\in J$, $t\in T$, $\delta\in D_{\sigma j}$, $c\in C_{j\sigma}$:

$$V_{jt}^{c}=V_{jt-1}^{c}+a_{jt}^{\bar{c}-}-a_{jt}^{c+}, \tag{13}$$

$$a_{jt}^{c+}=\min\left\{b_{jt}^{c} z_{\sigma_j\delta};\ V_{jt-1}^{c}+a_{jt}^{\bar{c}-}\right\}, \tag{14}$$

$$V_{jt}^{c}\ge 0, \tag{15}$$

$$H_{jt}^{c}=\max\left\{0;\ H_{jt-1}^{c}+a_{jt}^{c+}-p_{jt}^{c}\Delta t\right\}, \tag{16}$$

$$a_{j(t+\Delta\tau_j^c)}^{c-}=\min\left\{p_{jt}^{c}\Delta t;\ H_{jt-1}^{c}+a_{jt}^{c+}\right\},\ \text{if}\ i(c)>1, \tag{17}$$

$$a_{jt}^{\bar{c}-}=b_{jt}^{0} z_{\sigma_j\delta},\ \text{if}\ i(c)=1, \tag{18}$$

$$\sum_{t\in T_j} a_{j(t+\Delta\tau_j^c)}^{c-}=N_j z_{\sigma_j\delta},\ \text{if}\ i(c)=\left|C_{j\delta}\right|, \tag{19}$$

$$p_{jt}^{c}=\min_{k\in K_j^c}\left\{\frac{x_{jtk}^{c}}{r_{jk}^{c}\Delta\tau_j^{c}}\right\}; \tag{20}$$

– restrictions on the choice of protection scenarios:

$$\sum_{\delta\in D_\sigma} z_{\sigma\delta}=1,\ \sigma\in\Theta_T, \tag{21}$$

$$z_{\sigma\delta}\in\{0,1\},\ \delta\in D_\sigma,\ \sigma\in\Theta_T; \tag{22}$$

– general restrictions on the use of resources:

$$\sum_{j\in J_t}\sum_{\delta\in D_{\sigma_j}}\sum_{c\in C_{j\delta}} x_{jtk}^{c}\le X_k,\ k\in K^{I},\ t\in T, \tag{23}$$

$$\sum_{j\in J_t}\sum_{\delta\in D_{\sigma_j}}\sum_{c\in C_{j\delta}} x_{jtk}^{c}\le X_k+y_k,\ k\in K^{II},\ t\in T, \tag{24}$$

$$\sum_{j\in J_t}\sum_{\delta\in D_{\sigma_j}}\sum_{c\in C_{j\delta}} x_{jtk}^{c}\le y_{kt},\ k\in K^{III},\ t\in T, \tag{25}$$

$$y_{kt}\le X_k,\ t\in T,\ k\in K^{III}, \tag{26}$$

$$\sum_{t\in T} y_{kt}\le X_k^{\Sigma},\ k\in K^{III}; \tag{27}$$

– direct constraints on variables not listed above:

$$V_{jt}^{c}=0,\ H_{jt}^{c}=0,\ j\in J,\ \delta\in D_{\sigma_j},\ c\in C_{j\delta},\ t\notin T_j, \tag{28}$$

$$y_{kt}\ge 0,\ t\in T,\ k\in K^{III},\ y_k\ge 0,\ k\in K^{II}, \tag{29}$$

$$x_{jtk}^{c}\ge 0,\ k\in K,\ j\in J,\ t\in T_j,\ \delta\in D_{\sigma_j},\ c\in C_{j\delta}. \tag{30}$$

The following are the definitions and parameters of the model:

– T – a set of related time intervals of the same duration, over which the simulation is carried out;

– $t \in T$ – a separate time interval;

– Δt – duration of a separate time interval, which is the same for all intervals;

– Θ_T – a set of threat scenarios that operate on the set of time intervals T;

– $\sigma \in \Theta_T$ – separate threat scenario;

– $T_\sigma \subseteq T$ – a set of time intervals over which the action of the threat scenario σ is distributed. Let's assume that different threat scenarios act on different time intervals, thus the sets T_σ for different scenarios σ do not intersect;

– D_σ – a set of protection scenarios against threat scenario σ;

– $\delta \in D_\sigma$ – separate protection scenario;

– J – a set of all flights that must be carried out according to the schedule, on the set of time intervals T;

– $j \in J$ – a separate flight. The index j is uniquely tied to the time and day of the week (month) when the flight is performed. That is, flights with the same departure time and direction, which are performed on different days, are indicated in the model by different indices j;

– N_j – the number of passengers on flight j;

– $T_j \subset T$ – a set of time intervals that can be carried out during preparation for flight j;

– $J_t = \{j\} \in J | t \in T_j\}$ – a subset of flights for which preparation for execution is carried out at a certain interval $t \in T$;

– $\sigma_j \in \Theta T$ – threat scenario, the action of which occurs at the initial interval $t \in T_j$ flight j;

– Cj_δ – a set of checks that passengers of flight j must pass in an orderly manner according to the security scenario $\delta \in D_{\sigma_j}$;

– $c \in Cj_\delta$ – separate checks for passengers of flight j;

– $i(c)$ – checks by ordinal number c in the set $C_{j\delta}$;

– $\breve{c}$ – preliminary pre-test;

– $\left|C_{j\delta}\right|$ – the number of checks in the set $C_{j\delta}$;

– $\Delta\tau_j^c$ – the average time spent by a passenger of flight j directly on the verification process c;

– b_{jt}^0 – the number of passengers of flight j arriving at the airport at interval t (according to the passenger arrival model);

– b_{jt}^c – the number of passengers of flight j who are in the queue for check-in c at interval t, if they pass the preliminary check (according to the passenger behavior model);

– K – a set of airport resources used to conduct the inspection procedure;

– K^I, K^{II}, K^{III} – subsets of resource types (subsets do not overlap) that can be changed and redistributed in different ways;

– K_j^c – list of types of resources used to conduct the inspection c for flight j;

– r_{jk}^c – the average amount of resource k required to perform the verification procedure c one passenger of flight j;

– X_k – use of resource limit of type $k \in K$ at each interval $t \in T$;

– X_k^Σ – limit of total resource usage $k \in K^{III}$ at all intervals $t \in T$.

Here is a list of model variables, which can be divided into those used to make decisions and dependent and "technical" variables.

Variables used to make the decision:

– $z_{\sigma\delta} \in \{0,1\}$ – a Boolean variable indicating the choice (or not) of the protection scenario δ for the threat scenario σ;

– $x_{jtk}^c \geq 0$ – the number of resources of type k allocated for verification c for flight j at interval t.

Dependent and "technical" variable models:

– H_{jt}^c – the number of passengers of flight j who are waiting in line for screening c on the interval t;

– V_{jt}^c – the number of passengers on flight j who have already passed the preliminary check but have not yet queued for check c at interval t;

– a_{jt}^{c+} – the number of passengers of flight j who queue for inspection c at interval t;

– a_{jt}^{c-} – the number of passengers of flight j who completed check c at interval t;

– p_{jt}^c – throughput of the verification process of c passengers of flight j at interval t;

– y_k – additional resources of subset $k \in K^{II}$ that may be needed at the airport;

– y_{kt} – variable by which limited resources of subset $k \in K^{III}$ are distributed between intervals $t \in T$.

The meaning of constraints (13)–(30) is briefly presented below:

– (13) – balance of the number of passengers of flight j who have already passed the preliminary check, but have not yet queued for check c, at interval t;

– (14) – the number of passengers of flight j who are in line for inspection c under the protection scenario δ, at interval t is determined by the passenger behavior model and their number;

– (16) – balance of the number of passengers of flight j who are in the queue for check-in c at interval t;

– (17) – the number of passengers of flight j who have passed the check, c is determined by the throughput of the check and the presence of passengers in the queue. The end of the check c is shifted relative to the start by the time of the check $\Delta\tau_j^c$;

– (18) – the first check is preceded by the arrival of passengers at the airport, if the checks of the protection scenario δ are performed;

– (19) – the last check of flight j must end with all passengers of the flight if the checks of the protection scenario δ are performed;

– (20) – determination of the verification throughput c by the largest "scarce" resource;

– (21) – a protection scenario must be selected for each of the threat scenarios $\sigma \in \Theta_T$;

– (23)–(26) – restrictions on resource use at each interval $t \in T$;

– (27) – restriction on the total use of resources of type $k \in K^{III}$;

– (28) – the initial conditions for the dynamic balance equations (13) and (16).

– (15), (22), (29), (30) – direct constraints on the values of the variables. Subject to these constraints and the existence of an admissible solution in the model, all other variables will also take on a non-negative value according to the logic of the model.

The proposed model reflects the dynamics of passenger flow through airport procedures and will allow calculating the dynamic allocation of airport resources to perform screening procedures both during normal operation and when operating under threat conditions. The criterion is to minimize the maximum time spent by passengers on screening and waiting, and this criterion can also be considered one of the indicators of passenger service quality.

The model is dynamic and nonlinear with partially integer (Boolean) variables.

The demonstration of the calculation results of the proposed model (12)–(20) was carried out using data on passenger flows through Boryspil Airport, which were provided in the report of the Head of the State Aviation Service of Ukraine for 2019. [23]

According to the flight schedule in spring 2019, 560 flights were operated from the airport each week (153 domestic, 407 international). The number of departing passengers was about 48 thousand people per week or an average of about 6500 people per day [24]. These data were used to calculate an example of the flow of passengers through the airport, the distribution of this flow over time and the necessary provision of its support by airport resources according to the proposed model. Only departing passengers are considered.

Since the calculations using the model generate large amounts of numerical information, the results of these calculations are presented in the form of diagrams in the figures. Fig. 4 shows the value of the function $F(t)$, and Fig. 4–10 shows its components, $F_r(t)$, $F_p(t)$, $F_d(t)$, $F(t)_{v1}$, $F(t)_{v2}$, $F(t)_{v3}$, which are described for one day of Monday, calculated from the data [24].

Calculations were made taking into account the average workload of flights, which was 70 percent. The average total time spent directly on all security processes of checking one passenger is 5 minutes, and for registration 3 minutes.

The average throughput of the recording system and the security check system were increased by a factor of 1.2 from the minimum required level due to a possible increase in the use of venting resources.

According to the accepted indicator of the workload of flights on Monday, 7261 passengers depart from the airport. From the results obtained, it follows that the average time of 110 minutes that the passenger is at the airport is distributed between check-in, security checks, the boarding process and the free time before these processes, respectively, as follows: 7.4 minutes, 8.7 minutes, 9.5 minutes, 20.0 minutes, 27.6 minutes and 36.3 minutes.

The calculated duration of the processes also includes the waiting time in the queues before passing through these processes. Calculations were carried out according to the formula (11), which meets the criterion of optimality (12).

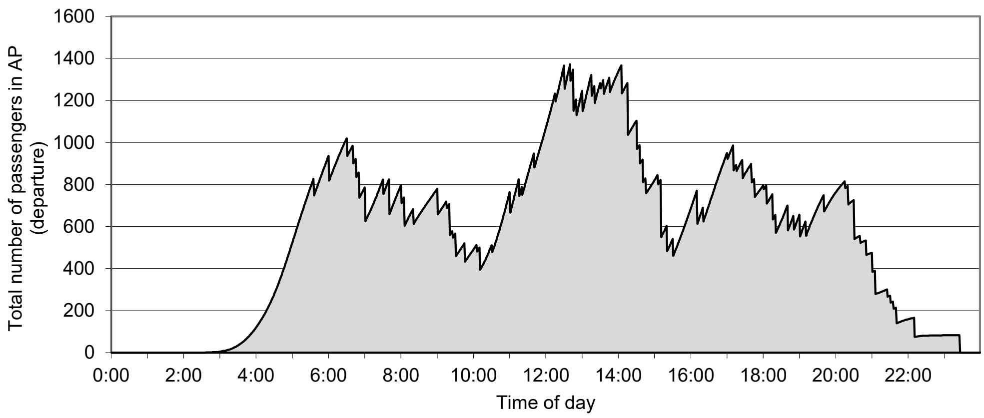

Fig. 4. Number of passengers staying at the airport and departing during Monday $F(t)$

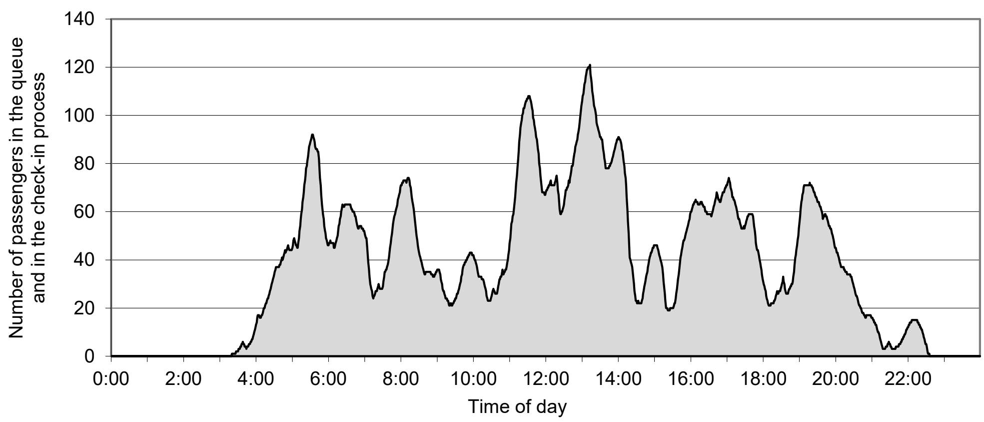

Fig. 5. Number of passengers queued for check-in and directly in the check-in process on Monday $F_r(t)$

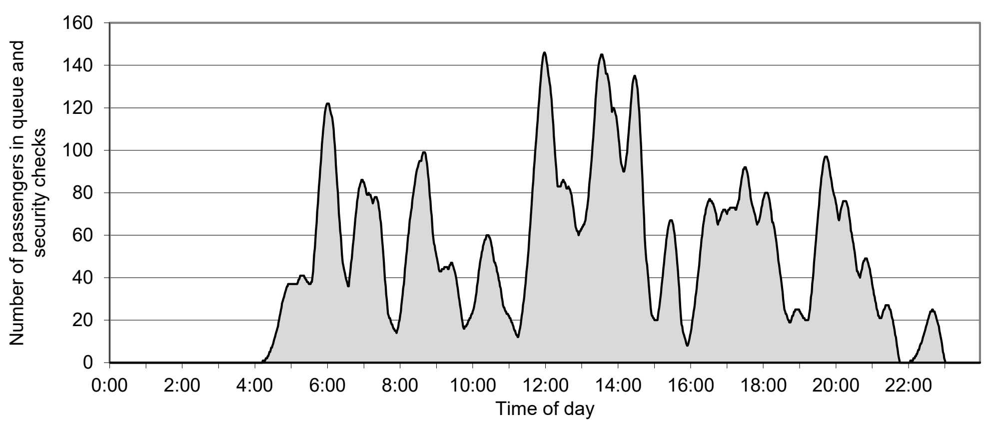

Fig. 6. Number of passengers queued for safety checks and directly in the process of checking on Monday $F_p(t)$

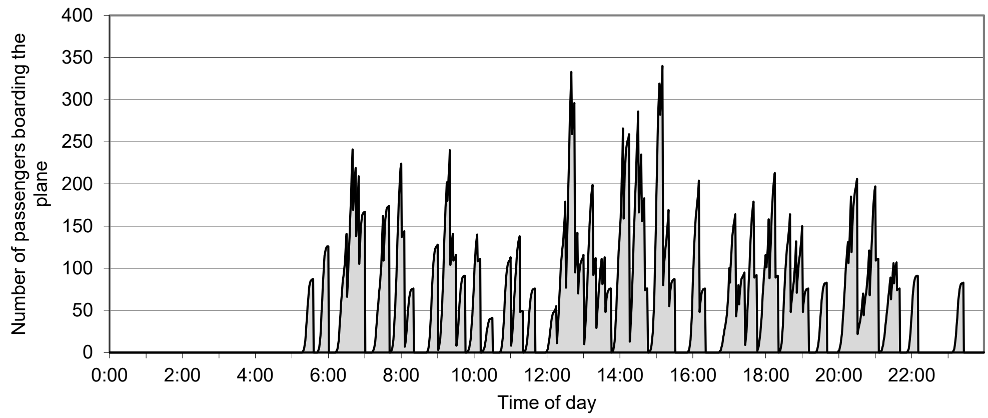

Fig. 7. Number of passengers queued to board and landing on Monday $F_d(t)$

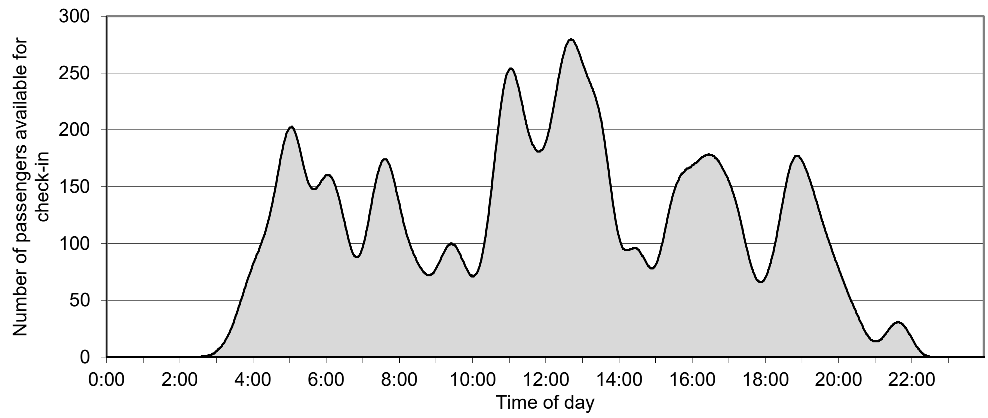

Fig. 8. Number of passengers with free time before check-in on Monday $F(t)_{v1}$

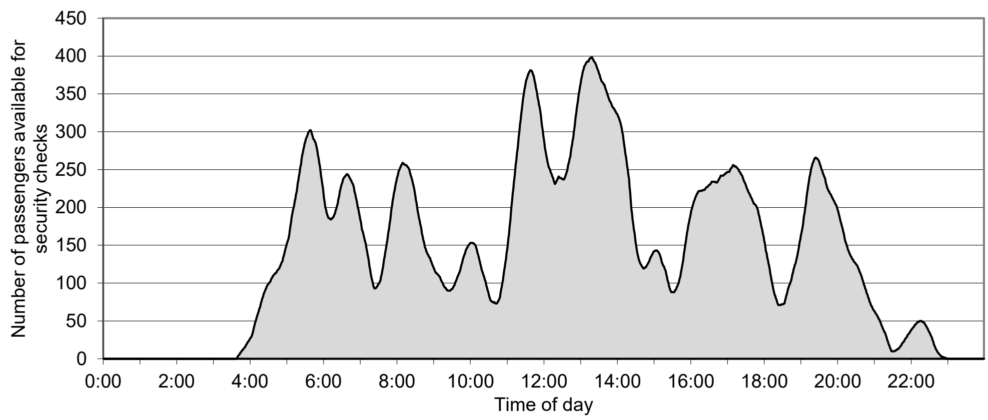

Fig. 9. Number of passengers with free time before passing security checks on Monday $F(t)_{v2}$

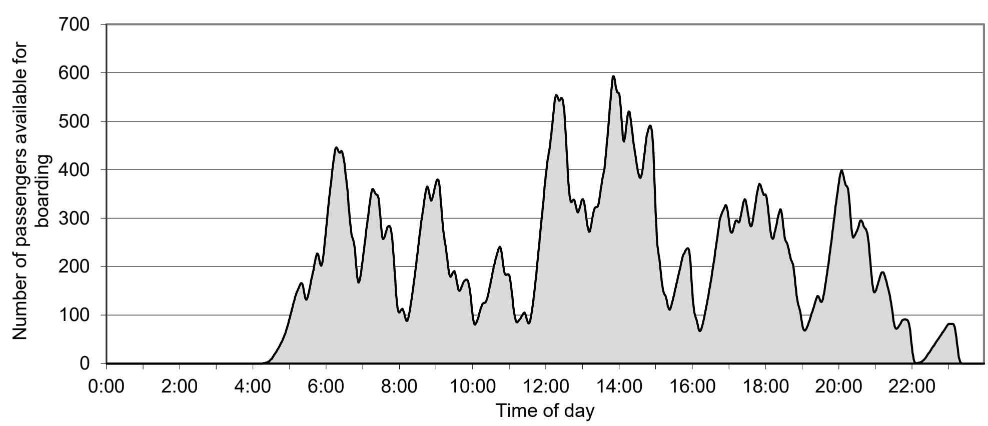

Fig. 10. Number of passengers having free time before boarding planes on Monday $F(t)_{v3}$

Along with a direct security check of the processes of registration of passengers, passport control, boarding the plane is also accompanied by security elements and can be considered as a process of ensuring security in general.

The average capacity of the registration process and security checks in the given example was increased by 1.2 times from the minimum required to meet the deadlines. This implies an increase in the use of relevant airport resources.

Also, these resources should include the relevant specialized and equipped areas of the airport, the time of work of the relevant specialists and the time of use of special equipment and controls.

Further, a study was conducted on how changes in the capacity of the security checks process affect the total time spent by one passenger in queues and directly in the processes of these checks.

This result was obtained after calculations according to the model (12)–(20) with the same input data and assumptions. It also takes into account variations in bandwidth with a coefficient from 1.0 to 2.0 and for three values of the average total time spent directly on all security checks of one passenger, namely: 3, 5 and 7 minutes. Fig. 11 shows the resulting dependencies.

The Fig. 11 shows that the time spent by one passenger in queues and directly in the processes of safety checks and which in the first version of the calculation was 8.7 minutes varies from 12.5 to 5 minutes.

It is noted that exceeding the average throughput by 2 times is a purely theoretical assumption. Since this would require a corresponding increase in airport resources, which in some periods of time may be scarce. Thus, the calculation results shown in Fig. 11 correspond to the following extreme cases of resource demand – for performing safety checks lasting an average of 7 minutes per passenger. If the capacity is exceeded by 2 times, the need for appropriate resources is 4.7 times greater than for performing safety checks lasting an average of 3 minutes per passenger and with the minimum sufficient process capacity to carry out everything within the established time frame. The possible excess for individual time intervals of the daily cycle of airport operation is due to the uneven flow of passengers.

But in the event of a threat, more thorough checks of passengers can be applied, which increases the average duration of checks of one passenger. And this requires a corresponding increase in the use of resources: an increase in the working time of relevant specialists, the use of equipment occupancy time and the possible use of additional space.

In the absence of additional resources, the process of checking all passengers of the flight may take longer than it is allotted, and this will lead to a delay in the departure of one or more flights.

Further, calculations are made that allow to investigate how an increase in the average time for checking one passenger for safety affects the time spent by one passenger in queues and directly in the processes of these checks, subject to limited resources for such checks.

Fig. 12 shows such dependence, as well as three additional dependencies, namely: the time spent in the queue, waiting for verification, resource shortages and the flight departure delay time, which is associated with an increased duration than the normative verification of all passengers in case of insufficient resources. Resource scarcity is shown as a percentage of the limited resource available; other results are presented as averages in minutes.

Thus, increasing the duration of safety checks for passengers can lead to several subjectively negative consequences for passengers. This includes increasing the time of the checks themselves, increasing the waiting time in queues for such checks and delaying the flight.

Fig. 12 shows the delay in flight departure, which is calculated for one flight and provided that passenger safety checks begin in accordance with the schedule. So, if additional security measures will be in effect for a long time and will concern all flights, then there will be an effect of accumulation of detikite of resources and there will be a greater delay of subsequent flights.

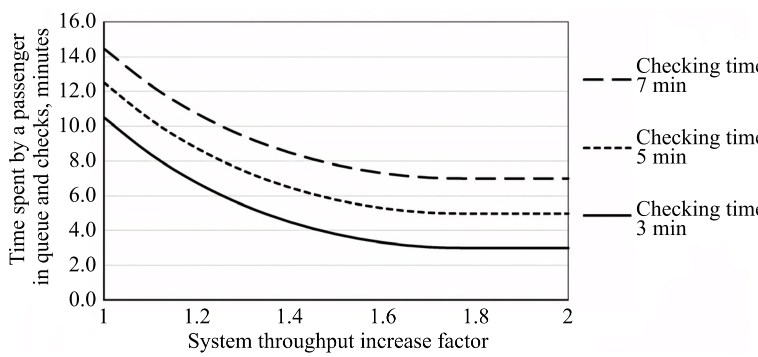

Fig. 11. The dependence of the time (in minutes) spent by one passenger in queues and directly in the processes of safety checks on the throughput of processes for 3 different durations of directly checks (average values are shown)

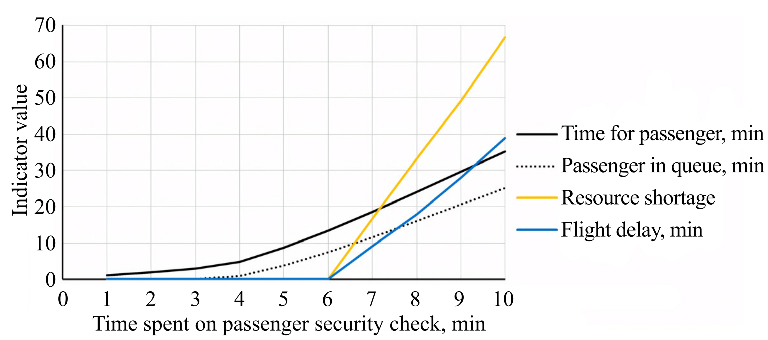

Fig. 12. Dependence of 4 indicators on changes in the average duration of checks for the safety of one passenger (in minutes)

Therefore, additional security measures should be coordinated with available and additional resources, taking into account the current flows of passengers at the airport, which allows to make a model (12)–(20).

6. Discussion of the results of the proposed air transport safety system

The vulnerability of air transport to the UIA implementation is of great importance in ensuring the safety of civil aviation, especially for the protection of infrastructure.

When considering the ATS components, the most vulnerable infrastructure objects were identified and the factors influencing the security of its components were determined, depending on the characteristics of their functioning.

It is determined that for the ATS component, the most vulnerable object of infrastructure is the airport, where the initial and final operations of the flight take place. Thus, airports provide security, regularity of flights, ground handling of air traffic at their initial and final stages. The prerequisite for the development of future security measures is the statistical data of world information on the implementation of UIA in airport terminals. Such analytics allows to identify the causes and effects of the factors of the UIA implementation, as well as to develop appropriate measures to prevent dangerous events in the future.

Considering the component of a special-purpose ATS, it can be seen that aviation security factors are specific (Fig. 1) for sectors of this component. It was found that the most vulnerable sector of special aviation is the aviation-chemical works in the agricultural sector, where it is necessary to carry out not only the safety of storage of aircraft, but it is also necessary to ensure proper storage of pesticides and fertilizers.

Thus, the study of aviation security becomes a priority in solving the issue of safe activities of civil aviation.

Since the airport is recognized as the main critical infrastructure facility where passenger flows are most processed, a mathematical model of the aviation security system at the airport has been developed.

The impact of security measures on the average time spent by passengers at the airport on the procedures for issuing departure is considered in accordance with the conditional time schedule of one passenger's stay at the airport and the processes of preparation for departure (Fig. 2). According to the scheme in Fig. 2, the flow of passengers $F(t)$ was divided into those who queued for check-in and baggage drop-off, but had not yet passed $F_r(t)$; who has queued for security, customs and passport control, but has not yet passed $F_p(t)$: who has queued to board the plane, but the plane has not yet departed $F_d(t)$ and passengers waiting for the start of the next procedure, use additional services at the airport $F(t)_{v1}$, $F(t)_{v2}$, $F(t)_{v3}$. These streams are represented by (1). The total average passenger stay at the airport is about 110 minutes.

The change in the speed of the procedures affects both the distribution of the number of passengers between the functions $F(t)_{v1}$, $F_r(t)$, $F(t)_{v2}$, $F_p(t)$, $F(t)_{v3}$, $F_d(t)$, and the distribution of the total time of the passenger's stay at the airport.

The proposed model includes the following security components: a set of potential threats that can be identified (z); a set of possible scenarios for the implementation of each threat (S_ζ); combining all threat scenarios because multiple scenarios do not intersect $\left(\Theta = \bigcup_{\zeta \in Z} S_\zeta\right)$; multiple threat protection scenarios for each threat scenario (D_σ).

External factors in relation to the model, which are the threat and the threat scenario, are also taken into account, and protection scenarios are selected. The threat appears and over time may change or disappear. The consequence of using a protection scenario for passengers may be: carrying out additional checks; increased time of procedures (checks); delay or postponement of departure for a considerable time; additional activities for different flights may be different.

The results of calculations of the proposed model (12)–(20) were carried out using data on passenger flows through Boryspil airport according to the flight schedule in the spring of 2019. 560 flights were operated from the airport every week (153 – domestic, 407 – international). The number of passengers who flew was about 48 thousand people weekly or an average of about 6500 people per day. These data were used to calculate an example of the flow of passengers through the airport, the distribution of this flow in time and the necessary provision of its maintenance with airport resources according to the proposed model. Only departing passengers were considered.

Along with a direct security check of the processes of registration of passengers, passport control, boarding the plane is also accompanied by security elements and can be considered as a process of ensuring security in general.

As a result of an increase in capacity by 1.2 times from the minimum required to meet the deadlines, it is assumed to increase the use of relevant airport resources. These resources should include the relevant specialized and equipped areas of the airport, the time of work of the relevant specialists and the time of use of special equipment and controls.

The results shown in Fig. 11 correspond to the following extreme cases of resource requirements – for performing safety checks lasting an average of 7 minutes per passenger. If the capacity is exceeded by 2 times, the need for appropriate resources is 4.7 times greater than for performing safety checks lasting an average of 3 minutes per passenger and with the minimum sufficient process capacity to carry out everything within the established time frame. The possible excess for individual time intervals of the daily cycle of airport operation is due to the uneven flow of passengers.

The results of the calculations shown in Fig. 12 show how an increase in the average time of checking one passenger for safety affects the time spent by one passenger in queues and directly in the processes of these checks. At the same time, the conditions of limited resources for such inspections were observed. Therefore, increasing the duration of safety checks for passengers can lead to several subjectively negative consequences for passengers. This includes increasing the time of the checks themselves, increasing the waiting time in queues for such checks and delaying the flight. Fig. 12 shows the delay in flight departure, which is calculated for one flight and provided that passenger safety checks begin in accordance with the schedule. So, if additional security measures will be in effect for a long time and will concern all flights, then there will be an effect of accumulation of deficit of resources and there will be a greater delay of subsequent flights.

The proposed model reflects the dynamics of the flow of passengers through the procedures at the airport and allows to calculate the dynamic distribution of airport resources to perform inspection procedures both during normal work and when working under threat conditions. At the same time, the optimization criterion is to minimize the longest time spent by passengers on checks and expectations, and this criterion can also be considered one of the indicators of the quality of passenger service. The model is dynamic and nonlinear with partially integer (Boolean) variables.

The obtained results of calculations on the model (12)–(20) allow to coordinate additional security measures with available and additional resources, taking into account the current flows of passengers at the airport. It should also be noted some limitations (13)–(30), consisting in the resistance of decisions to changes in the factors of influence on the safety measures of air transport.

The disadvantage of this study is that it occurs in conditions of uneven, heterogeneous and unstable environment, which protects the critical infrastructure.

The development of this study may consist in the development of a model of aviation security for the subsystem "Special Forces Aviation", as well as in the context of changes in the standardization of aviation security and ATS capabilities.

7. Conclusions

1. It is revealed that the prerequisite for the development of future security measures is the statistical data of world information on the UIA implementation in airport terminals. Such analytics made it possible to identify the causes and impact of the factors of UIA implementation, as well as to develop appropriate measures to prevent dangerous events in the future. Considering the component of special aviation, it turned out that the most vulnerable sector of special aviation is aviation-chemical work in the agricultural sector, where it is necessary to carry out not only the safety of storage of aircraft, but also to ensure proper storage of pesticides and fertilizers.

2. A mathematical model has been developed that reflects the dynamics of the flow of passengers during the passage of mandatory procedures at the airport and allows to calculate the dynamic distribution of airport resources to perform inspection procedures both during normal work and when working under threat conditions. At the same time, the optimization criterion is to minimize the total time spent by passengers at the airport for checks and waiting in queues. Also, this criterion can be considered one of the indicators of the quality of passenger service. The calculation of the flow of passengers through the airport, the distribution of this flow in time and the necessary support of this flow with the resources of the airport according to the model is made. This makes it possible to investigate how an increase in the average time of checking one passenger for safety affects the time spent by one passenger in queues and directly in the processes of these checks, subject to limited resources for such checks. Thus, additional security measures should be coordinated with available and additional resources, taking into account the current flows of passengers at the airport, this is what the model allows to do.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship or other nature that could affect the study and its results presented in this article.

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Data availability

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Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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