ISSN 2720-197X / eISSN 2956-3380

Krzysztof CUR
Polish Air Force University
e-mail: k.cur@law.mil.pl; ORCID: 0000-0003-4552-445X

Paweł GOŁDA
Polish Air Force University
e-mail: p.golda@law.mil.pl; ORCID: 0000-0003-4066-7814

Mariusz IZDEBSKI
Warsaw University of Technology
e-mail: mariusz.izdebski@pw.edu.pl; ORCID: 0000-0002-9157-7870

Justyna TOMASZEWSKA
Polish Air Force University
e-mail: j.tomaszewska@law.mil.pl; ORCID: 0000-0001-6883-7235

DOI: 10.55676/asi.v4i2.92

MINIMIZING THE RISK OF ACCIDENTS IN-GROUND AIRPORT OPERATIONS CARRIED OUT BY AIRCRAFT

MINIMALIZACJA RYZYKA WYPADKÓW W NAZIEMNYCH OPERACJACH LOTNISKOWYCH REALIZOWANYCH PRZEZ STATKI POWIETRZNE

Abstract

The paper presents the problem of managing traffic safety on the airport apron. The article aims to develop a method to minimize the risk of hazardous events in ground airport operations carried out by aircraft during take-off or landing. The development of the method required defining a decision-making model for accident risk management in airport ground operations. The model designated in this work is a decision model consisting of the following stages, i.e. development of input data, decision variables, constraints and criterion functions. Collision-free aircraft traffic control is essential in managing traffic safety on the airport apron. A new approach to managing traffic safety on the airport apron presented in this work is to minimize dangerous situations between aircraft, and ground support vehicles. An ant algorithm was developed to determine collision-free flight routes for aircraft on the airport apron. The method based on the ant algorithm was verified on data from the Chopin airport in Warsaw. The verification confirmed its high effectiveness. The movement of ground service vehicles was modeled using the GlobSim traffic simulator.

Keywords: ant algorithm, GlobSIM simulator, ground service vehicles, risk analysis

Streszczenie

W pracy przedstawiono problem w zarządzaniu bezpieczeństwem ruchu na płycie lotniska. Celem artykułu było opracowanie metody minimalizującej ryzyko zdarzeń niebezpiecznych w naziemnych operacjach lotniskowych realizowanych przez statki powietrzne. Opracowanie metody wymagało zdefiniowania modelu decyzyjnego zarządzania ryzykiem wypadków w naziemnych operacjach lotniskowych. Wyznaczony w pracy model jest modelem decyzyjnym składającym się z następujących etapów, tj. opracowanie danych wejściowych, zmiennych decyzyjnych, ograniczeń oraz funkcji kryterium. Istotne znaczenie w zarządzaniu bezpieczeństwem ruchu na płycie lotniska ma bezkolizyjne sterowanie ruchem statków powietrznych. W celu wyznaczania tras jazdy statków powietrznych po płycie lotniska opracowano algorytm mrówkowy. Metodę bazująco na algorytmie mrówkowym zweryfikowano. Weryfikacja potwierdziła wysoką jej skuteczność. Weryfikacji metody dokonano na danych rzeczywistych z lotniska Chopina w Warszawie. Ruch pojazdów obsługi naziemnej został zamodelowany przy wykorzystaniu symulatora ruchu GlobSim.

Słowa kluczowe: algorytm mrówkowy, symulator GlobSIM, pojazdy obsługi naziemnej, analiza ryzyka

Artykuł wpłynął do redakcji: 26.08.2023 / Zatwierdzono do publikacji: 30.12.2023

1. INTRODUCTION

The research conducted in this work focuses on issues related to traffic safety management on the airport runway. Collision-free control of the movement of aircraft performing take-off or landing operations is of significant importance in managing traffic safety on the airport apron. The article aims to develop a method to minimize the risk of dangerous events, e.g. accidents in ground airport operations carried out by aircraft. Designing the method required defining a decision model and an optimization algorithm. The decision-making model for accident risk management in airport ground operations was developed to determine collision-free flight routes for aircraft on the airport apron.

Dangerous threats on the airport apron result from two situations, i.e. a collision of an aircraft with another aircraft or a aircraft with other traffic participants, e.g. ground service vehicles[1]. To minimize the risk of collision between aircraft, the model introduced a limitation that blocks the appearance of two or more aircraft in a given place simultaneously.

However, minimizing collisions between the aircraft and other ground traffic participants is problematic because the driving routes of other road participants are unknown and difficult to determine due to their random nature[2]. To illustrate the movement of other participants on the airport apron, e.g. ground service vehicles, a parameter was introduced that determines the probability of occupying a given section of the airport apron[3]. This probability was defined by the theoretical distribution specified in the Statistica 13 program. Determining the probability distribution of an airport apron section occupancy is based on statistical inference regarding matching empirical and theoretical distributions. The random variable describing this distribution is presented as the moment of occupation of a given section of the airport apron by vehicles other than aircraft. The occupancy moments of the sections were generated based on the GlobSIM simulator[4], which is a tool intended for research and analysis of traffic management processes on the airport apron.

In the decision-making model, the criterion function is the function that minimizes the probability of an aircraft collision with ground support vehicles at the time of take-off or landing.

1 P. Gołda, T. Zawisza, M. Izdebski, Evaluation of efficiency and reliability of airport processes using simulation tools, "Eksploatacja i Niezawodność" 2021, vol. 23, no. 4, pp. 659–669.

2 M. Izdebski, P. Gołda, T. Zawisza, The Use of Simulation Tools to Minimize the Risk of Dangerous Events on the Airport Apron, [in:] Advanced Solutions and Practical Applications in Road Traffic Engineering: conference proceedings, E. Macioszek, A. Granà, G. Sierpiński (ed.), Lecture Notes in Networks and Systems, 2023, vol. 604, Springer, pp. 91–107, DOI: 10.1007/978-3-031-22359-4_6.

3 M. Izdebski, P. Gołda, T. Zawisza, The use of the ant algorithm in the model of safety management of the traffic organization at the apron, "Journal of KONBiN" 2022, vol. 52, no. 2, pp. 63–76.

4 Certificate granted to the software by the Civil Aviation Office on September 17, 2018 No. PL/FISP-TO/PWBISEK.

 DOI: 10.55676/asi.v4i2.92

The new approach presented in the work is to consider collisions between aircraft and other traffic participants, e.g., ground service vehicles, when determining aircraft routes on the airport apron. An ant algorithm was developed to assess aircraft routes on the airport apron. The selected algorithm's advantage over other optimization algorithms is its short computational time[5]. The ant algorithm is one of the algorithms recommended in the literature to determine vehicle routes[6]. The developed ant algorithm has been calibrated, and its input parameters have been determined. Algorithm calibration involves selecting the input parameters of the algorithm that will generate the best solution. The effectiveness of the ant algorithm was verified by indicating incorrectly generated routes for the aircraft's collision with the ground service vehicle. The method was demonstrated on actual data from the Chopin Airport in Warsaw.

The result of the described works is the presentation of a comprehensive approach to managing traffic safety on the airport apron, considering the traffic situation of aircraft determined by the ant algorithm and the ground service vehicles using the GlobSIM simulator.

2. LITERATURE ANALYSIS

Minimizing the risk of accidents in airport ground operations carried out by aircraft is a decision-making problem that is part of the broadly understood topic of airport safety management[7]. The airport apron is where dangerous collision situations often occur between road users[8].

Taxiing operations of an aircraft on the apron are essential to the transport process[9]. The publication's authors[10] presented a detailed review of research on aviation operations in the context of planning and determining aircraft routes on the airport apron. As part of taxiing operations, aircraft move within the airport using a network of roads for various purposes. The execution times of these operations affect the execution times of take-off and landing operations of other aircraft. Therefore, they may limit the airport's capacity[11]. Consequently, it is essential to plan traffic on the

5 M. Izdebski, M. Jacyna, An Efficient Hybrid Algorithm for Energy Expenditure Estimation for Electric Vehicles in Urban Service Enterprises, "Energies" 2021, vol. 14, no. 7, pp. 1–23.

6 M. Dorigo, L.M. Gambardela, Ant Colonies for the Travelling Salesman Problem, "BioSystems" 1997, vol. 43, pp. 73–81.

7 J. Fiuk, N. Chamier-Gliszczynski, M. Jacyna, M. Izdebski, Energy Efficiency of Transport Tasks Performed by the Air SAR System in the Baltic Sea: Case Study, "Energies" 2022, no. 15(2), p. 643.

8 G. Andreatta, L. Brunetta, Multiairport Ground Holding Problem: A Computational Evaluation of Exact Algorithms, "Operations Research" 1998 , vol. 46(1), pp. 57–64.

9 A. Agustín, A. Alonso-Ayuso, L. F Escudero, C. Pizarro, On air traffic flow management with rerouting, "Eur. J. Oper. Res." 2012, t. 219, no. 1, pp. 167–177.

10 K.K.H. Ng, C.K.M. Lee, F.T.S. Chan, Y. Lv, Review on meta-heuristics approaches for airside operation research, "Applied Soft Computing" 2018, vol. 66, pp. 104–133.

11 G. Andreatta, G. Romanin-Jacur, Aircraft Flow Management under Congestion, "Transp. Sci." 1987, vol. 21, no. 4, pp. 249–253.

airport apron in such a way as to minimize traffic intensity during take-off or landing of aircraft[12].

In managing traffic safety on the airport apron, it is essential to determine collision-free driving routes for both aircraft and ground service vehicles[13]. Collision-free aircraft routes are the basis for developing TCA (Traffic count area) aircraft take-off and landing schedules[14]. The authors of the publication[15] studied the problem of real-time aircraft planning routing for TCA to minimize the maximum delay to mitigate the effects of severe traffic disruptions. This problem was modelled as a scheduling problem and solved using a commercial solver. In the publication[16], the authors studied a similar scheduling problem for TCA and proposed heuristic and accurate algorithms.

Minimizing the risk of accidents in airport ground operations is often analysed in the context of the ARSP (Airport Runway Scheduling Problem)[17]. This problem aims to determine the optimal order in which aircraft land on a runway to improve runway utilization. Research on ARSP often focuses on the process of landing aircraft. Hence, it is called the aircraft landing problem.

Minimizing the risk of accidents in ground-based airport operations is difficult due to the stochastic aspect of ground-based airport operations[18]. For example, stochastic approaches require information about the probability distribution of take-off and landing times, which an adequate amount of historical data can determine.

The risk of accidents in ground-based airport operations is often analysed in the context of the GHP (Ground-Holding Problem). This problem can be defined as a problem in which it is determined for a given network of aircraft how long each aircraft must be held on the ground before departure to minimize the costs incurred in connection with delays for the entire network of aircraft, taking into account the capacity of a given airport and departure order[19].

12 M.O. Ball, R. Hoffman, A.R. Odoni, R. Rifkin, A Stochastic Integer Program with Dual Network Structure and Its Application to the Ground-Holding Problem, "Oper. Res." 2003, vol. 51, no. 1, pp. 167–171.

13 J.A. Bennell, M. Mesgarpour, C.N. Potts, Airport runway scheduling, "Ann Oper Res" 2013, vol. 204, no. 1, pp. 249–270.

14 M. Samà, A. D'Ariano, F. Corman, D. Pacciarelli, Coordination of scheduling decisions in the management of airport airspace and taxiway operations, "Transportation Research Part A: Policy and Practice" 2018, vol. 114, pp. 398–411.

15 M. Samà, A. D'Ariano, P. D'Ariano, D. Pacciarelli, Optimal aircraft scheduling and routing at a terminal control area during disturbances, "Transportation Research Part C: Emerging Technologies" 2014, vol. 47, pp. 61–85.

16 A. D'Ariano, D. Pacciarelli, M. Pistelli, M. Pranzo, Real-time scheduling of aircraft arrivals and departures in a terminal maneuvering area, "Networks" 2015, vol. 65, no. 3, pp. 212–227.

17 T. Fahle, R. Feldmann, S. Götz, S. Grothklags, B. Monien, The Aircraft Sequencing Problem, "Computer Science in Perspective", Springer 2023, vol. 2598, pp. 152–166.

18 R.A. Bihar, A conceptual solution to the aircraft gate assignment problem using 0, 1 linear programming, "Computers & Industrial Engineering" 1990, vol. 19, no. 1, pp. 280–284.

19 P.B. Liu, M. Hansen, A. Mukherjee, Scenario-based air traffic flow management: From theory to practice, "Transp. Res. Part B Methodol." 2008, vol. 42, no. 7, pp. 685–702.

 DOI: 10.55676/asi.v4i2.92

Optimization algorithms are used to manage traffic safety on the airport apron. The readiness to perform the task of aircraft used for cadets was presented in the work[20]. The work[21] presents an ant colony optimization algorithm and a fuzzy logic algorithm to manage air traffic flow. However, in the publication[22], dynamic programming was used to solve the GHP (Ground-Holding Problem). In the publication[23] the ARSP (Airport Runway Scheduling Problem) was solved by using a hybrid particle swarm optimization algorithm. Simulation methods are also used to manage airport traffic safety[24, 25].

Considering the above literature analysis, there is no comprehensive approach to minimizing the risk of accidents in-ground airport operations performed by aircraft. Most publications present the problem of reducing the risk of accidents only between aircraft. Considering other traffic participants on the airport apron, e.g. ground service vehicles are omitted. In the work, the authors presented the problem of minimizing the risk of accidents in-ground airport operations carried out by aircraft in a holistic way, taking into account both collision situations in the aircraft-aircraft and aircraft-vehicle relationship, and thus filling the research gap regarding the lack of a comprehensive analysis of the researched topic.

3. THE DECISION-MAKING MODEL FOR ACCIDENT RISK MANAGEMENT IN AIRPORT GROUND OPERATIONS

Determining collision-free flight routes for aircraft on the airport apron is important in managing the risk of accidents in airport ground operations[26]. To resolve these driving routes, a decision model was developed to minimize the probability of dangerous events occurring during the arrival or departure of aircraft.

To avoid collision situations involving ground service vehicles, a variable defined the theoretical probability distribution of a given section of the airport apron occupied by these vehicles. Collision situations with other aircraft have been minimized by blocking the appearance of two aircraft simultaneously at the same point on the route. Aircraft routes should be designated in such a way as to reduce the likelihood

20 K. Cur, M. Zieja, T. Czerwiński, J. Tomaszewska, Comparison of readiness to perform the task of aircraft used for cadet training, Proceedings of the 31st European Safety and Reliability Conference, ESREL 2021, https://doi.org/10.3390/aerospace9010014, pp. 337–343.

21 C. Ntakolia, D.V. Lyridis, A n − D ant colony optimization with fuzzy logic for air traffic flow management, "Oper. Res." 2022, vol. 22, pp. 5035–5053.

22 M. Terrab, A.R. Odoni, Strategic Flow Management for Air Traffic Control, "Oper. Res." 1993, vol. 41, no. 1, pp. 138–152.

23 B.S. Girish, An efficient hybrid particle swarm optimization algorithm in a rolling horizon framework for the aircraft landing problem, "Applied Soft Computing" 2016, vol. 44, pp. 200–221.

24 O. Čokorilo, Human factor modelling for fast-time simulations in aviation, "Aircr. Eng. Aerosp. Technol. Int. J." 2013, vol. 85, no. 5, pp. 389–405.

25 M. Izdebski, P. Gołda, T. Zawisza, The use of simulation tools to minimize the risk of dangerous events on the airport apron, Lecture Notes in Networks and Systems, 2023, 604 LNNS, https://doi.org/10.1007/978-3-031-22359-4_6, pp. 91–107.

26 J.E. Beasley, M. Krishnamoorthy, Y.M. Sharaiha, D. Abramson, Scheduling Aircraft Landings–The Static Case, "Transportation Science" 2000, vol. 34, no. 2, pp. 180–197.

of sections of the route being occupied by ground service vehicles. The model input data is presented in Table 3.1.

Table 3.1. Symbols used in the decision model

Symbol	Meaning
k	An end runway point, where k is an element of the set K
a	A place where an aircraft lands on an airport apron, a is an element of the set A
i,i',i''	Intermediate points (intersections), where i,i',i'' are elements of the set I
p	Aircraft parking points on the apron, where p is an element of the set P
v	An aircraft, where v is an element of the set V
$ts1\ (p,i,v)$	Aircraft travel time between a parking and an intermediate point
$tl1\ (i,p,v)$	Aircraft travel time between an intermediate and a parking point
$t2(i, i',v)$	Aircraft travel time between intermediate points
$ts3(i,k,v)$	Aircraft travel time between an intermediate point and a runway end point
$tl3(a,i,v)$	Aircraft travel time between the point where the aircraft lands on an apron and an intermediate point
$tp(v)$	Aircraft arrival time
$to(v)$	Aircraft departure time
R	Level of acceptable accident risk
$p(E(p,i))$	The probability of occupancy of a section by ground service vehicles between a parking point and an intermediate point
$p(E(i,p))$	The probability of a section occupancy by ground service vehicles between an intermediate point and a parking point
$p(E(i,i'))$	The probability of a section occupancy by ground service vehicles between intermediate points
$p(E(i,k))$	The probability of a section occupancy by ground service vehicles between an intermediate point and a runway end point
$p(E(a,i))$	The probability of a section occupancy by ground service vehicles between an aircraft landing place on an apron and an intermediate point
T_{max}	Time an apron is occupied by an aircraft

Source: own work.

A random variable determining the probability distribution of a given section of the apron occupied by ground service vehicles was defined as the moment of appearance of a ground service vehicle on a given section of the route. Therefore, the aircraft must appear on a given route section when the probability of the ground service vehicle occupying the route section is minimal. The movement characteristics of ground service vehicles were determined based on the GlobSIM traffic simulator. In contrast, the movement characteristics of aircraft were selected based on the decision-making model for accident risk management in ground airport operations developed in this work. To simplify the model, it was assumed that the points at which aircraft land on the airport apron are known. The arrival time is interpreted as when the aircraft lands on the airport apron, and the departure time is when the aircraft leaves the parking space.

Decision variables take the form:

 DOI: 10.55676/asi.v4i2.92

$xs1(p,i,v)$ – the connection between a stop point and an intermediate point made by a given aircraft, if $xs1(p,i,v) = 1$ there is a connection;

$xl1(i,p,v)$ – the connection between an intermediate point and a stop point made by a given aircraft, if $xl1(i,p,v) = 1$ there is a connection;

$x2(i,i',v)$ – the connection between intermediate points made by a given aircraft, if $x2(i,i',v) = 1$ there is a connection;

$xs3(i,k,v)$ – the connection between an intermediate point and a runway end point, if $xs3(i,k,v) = 1$ there is a connection;

$xl3(a,i,v)$ – the connection between a landing place of the aircraft on an apron and an intermediate point, if $xl3(a,i,v) = 1$ there is a connection.

The following limitations are distinguished in the decision model:

– maximum time of the apron being occupied by aircraft ((1) – in the case of take-off, (2) – in the case of landing):

$$\forall\ v \in \boldsymbol{V},\ i \in \boldsymbol{I},\ p \in \boldsymbol{P}, k \in \boldsymbol{K}$$

$$xs1(p,i,v) \cdot ts1\,(p,i,v) + \sum_{i' \in I} \sum_{i'' \in I} x2(i',i'',v) \cdot t2(i',i'',v) + xs3(i,k,v) \cdot ts3(i,k,v) \leq Tmax \tag{1}$$

$$\forall\ v \in \boldsymbol{V},\ i \in \boldsymbol{I},\ a \in \boldsymbol{A},\ p \in \boldsymbol{P}$$

$$xl3(a,i,v) \cdot tl3(a,i,v) + \sum_{i' \in I} \sum_{i'' \in I} x2(i',i'',v) \cdot t2(i',i'',v) + xl1(i,p,v) \cdot tl1\,(i,p,v) \leq Tmax \tag{2}$$

– permissible risk of accident ((3) – in the case of take-off, (4) – in the case of landing):

$$\forall\ v \in \boldsymbol{V},\ i \in \boldsymbol{I},\ p \in \boldsymbol{P}, k \in \boldsymbol{K}$$

$$xs1(p,i,v) \cdot p(E(p,i)) \cdot \prod_{i' \in I} \prod_{i'' \in I} x2(i,i',v) \cdot p(E(i',i'')) \cdot xs3(i,k,v) \cdot p(E(i,k)) \leq R \tag{3}$$

$$\forall\ v \in \boldsymbol{V},\ i \in \boldsymbol{I},\ a \in \boldsymbol{A},\ p \in \boldsymbol{P}$$

$$xl3(a,i,v) \cdot p(E(a,i)) \cdot \prod_{i' \in I} \prod_{i'' \in I} x2(i,i',v) \cdot p(E(i',i'')) \cdot xl1(i,p,v) \cdot p(E(i,p)) \leq R \tag{4}$$

– the appearance of aircraft in one place and time is impossible; the model takes into account various combinations of collisions between aircraft, e.g. during the take-off of several aircraft, the landing of several aircraft, in the event of a collision between a landing aircraft and a taking-off aircraft:

$$\forall\ v\in\boldsymbol{V},\ i\in\boldsymbol{I}, p\in\boldsymbol{P}, k\in\boldsymbol{K},\ a\in\boldsymbol{A},\ v\neq v'$$

$$to(v)+xs1(p,i,v)\cdot ts1\,(p,i,v)+\sum_{i'\in I}\sum_{i''\in I}x2\left(i',i'',v\right)\cdot t2\left(i',i'',v\right)$$
$$\neq tp(v')+xl3(a,i,v')\cdot tl3(a,i,v')+\sum_{i'\in I}\sum_{i''\in I}x2\left(i',i'',v'\right)\cdot t2\left(i',i'',v'\right)$$

(5)

The criterion functions minimizing the probability of ground service vehicles occupying the entire route taken by individual aircraft are presented as ((6) – in the case of take-off, (7) – in the case of landing):

$$\forall\ v\in\boldsymbol{V},\ i\in\boldsymbol{I}, p\in\boldsymbol{P}, k\in\boldsymbol{K}$$

$$F1=xs1(p,i,v)\cdot p(E(p,i))\cdot\prod_{i'\in I}\prod_{i''\in I}x2(i,i',v)\cdot p(E(i',i''))\cdot xs3(i,k,v)\cdot p(E(i,k))\longrightarrow min$$

(6)

$$\forall\ v\in\boldsymbol{V},\ i\in\boldsymbol{I},\ a\in\boldsymbol{A},\ p\in\boldsymbol{P}$$

$$F2=xl3(a,i,v)\cdot p(E(a,i))\cdot\prod_{i'\in I}\prod_{i''\in I}x2(i,i',v)\cdot p(E(i',i''))\cdot xl1(i,p,v)\cdot p(E(i,p))\longrightarrow min$$

(7)

4. THE ANT ALGORITHM MINIMIZING THE RISK OF ACCIDENTS ON AN AIRPORT APRON

The developed ant algorithm determines the driving routes of aircraft characterized by the minimum probability of these routes being occupied by ground service vehicles. The task of the developed ant algorithm is to find such settings of decision variables for which the criterion functions (6), (7) reach minimum values. The ant algorithm introduces an artificial ant, whose task is to determine the driving routes of all aircraft on the airport apron. A graphical interpretation of the ant's route is shown in Fig. 1. The ant's route consists of three layers. The starting point of the ant's route in determining the starting aircraft driving routes is the parking places of these aircraft on the airport apron, which are collected in layer I. In layer II, intermediate points of the route with the interpretation of intersections on the airport apron are included. In contrast, in layer III there are points with the interpretation of the end of the runway. In the case of aircraft landing, layer III assumes the interpretation of where these aircraft land on the runway.

 DOI: 10.55676/asi.v4i2.92

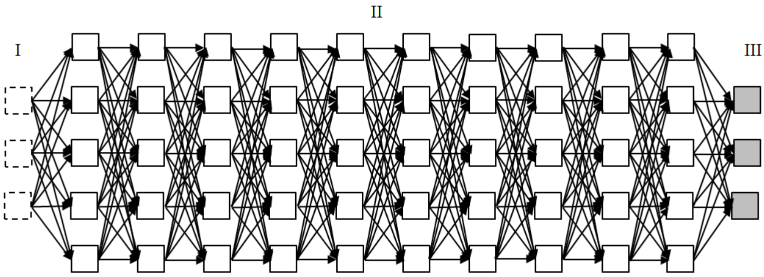

Fig. 1. Elements of an ant's route

Source: own work.

In the case of an aircraft departure, the starting point of the ant's route is the interpretation of the parking space on the airport apron, and in the case of arrival, the interpretation of an aircraft landing place. The ant's further route and, thus, the selection of subsequent route points occurs with a certain probability[27]:

$$PR^{mr}{}_{yz}(t) = \begin{cases} \dfrac{[\tau_{yz}(t)]^{\alpha} \cdot [\eta_{yz}(t)]^{\beta}}{\sum_{l \in \Omega^{mr}} [\tau_{yl}(t)]^{\alpha} \cdot [\eta_{yl}(t)]^{\beta}} & , z \in \Omega^{mr} \\ 0 & , z \notin \Omega^{mr} \end{cases} \quad (8)$$

where:

$\tau_{yz}(t)$ – the intensity of the pheromone trace between the y-th point of the ant's route and the z-th point in the t-iteration of the algorithm, $\eta_{yz}(t)$ – heuristic information:

$$\eta_{yz}(t) = \frac{1}{p(y,z)} \quad (9)$$

where:

$p(y,z)$ – the probability of network sections being occupied;

α, β – the influence of pheromones and heuristic data on the behavior of ants;

Ω^{mr} – the set of all point elements of the airport apron, l – potential points of the ant's route taken into account when selecting the next point of the ant's route.

A single ant's routes have an interpretation of all aircraft driving routes. Once all ants in the population have finished building routes, the pheromone trail is updated. Initially, it is assumed that the trace on the connections between route points is uniformly strong. In subsequent iterations, the pheromone trace is calculated according to the formula[28]:

27 M. Dorigo, L.M. Gambardela, Ant Colony System: A cooperative learning approach to the traveling salesman problem, "IEEE Transactions on Evolutionary Computation" 1997, vol. 1(1), pp. 53–66.

28 M. Dorigo, T. Stutzle, Ant Colony Optimization, Bradford Books 2004.

$$\tau_{yz}(t+1)=(1-\rho)\tau_{yz}(t)+\sum_{mr=1}^{MR}\Delta\tau_{yz}{}^{mr}(t) \tag{10}$$

where:

mr – another ant in the anthill $mr \in MR$;

ρ – pheromone volatilization rate ($0 < \rho \le 1$);

$\tau_{yz}\ (t+1)$ – for the first iteration, Pheromone gain takes a value at each connection equal to τ_0.

The first component of formula (9) determines the pheromone volatilization rate, while the second determines the pheromone gain and takes a specific value when the ant uses the section (y,z), otherwise 0, i.e.:

$$\Delta\tau_{yz}{}^{mr}(t)=\{\frac{1}{P^{mr}(t)}-K1^{mr}(t)-K2^{mr}(t)-K3^{mr}(t)\ 0 \tag{11}$$

where:

$P^{mr}(t)$ – the probability of the ant's entire route being occupied by ground service vehicles, calculated based on formulas (6) and (7);

$K1^{mr}(t)$ – penalty for exceeding the limits regarding the maximum time of occupation of the airport apron by aircraft (1), (2) in the route created by the ant in the algorithm iteration, it is assumed that this penalty is half of the pheromone accumulated on the route;

$K2^{mr}(t)$ – penalty for exceeding the permissible risk of an accident (3), (4) in the route created by the ant in the algorithm iteration, it is assumed that this penalty is half of the pheromone accumulated on the route;

$K3^{mr}(t)$ – penalty for exceeding the limitation regarding the appearance of aircraft in one place and time (5) on the route created by the ant in the iteration of the algorithm; it is assumed that this penalty is half of the pheromone accumulated on the route.

The ant algorithm is iterative and runs until a stop condition is reached. The stopping condition is a fixed number of iterations. The number of ants in the population and the number of iterations are determined at the beginning of the algorithm implementation. The main steps of the ant algorithm are shown in Table 4.1.

 DOI: 10.55676/asi.v4i2.92

Table 4.1. Steps of the ant algorithm

Steps	Description
Step 1	The ant determines the connection: the aircraft parking point – an intermediate point for aircraft taking off or the aircraft landing point – an intermediate point for landing aircraft.
Step 2	Selecting subsequent connections according to the defined probability (8) until the ant completes the route of a single aircraft.
Step 3	Repeat step 1 for the next aircraft until all aircraft routes have been completed.
Step 4	Repeating steps 1–3 for all ants in the population.
Step 5	Pheromone update (10).
Step 6	Repeating steps 1–5 until the algorithm reaches a stopping condition. The final solution is the route of the ant with the highest pheromone intensity among all routes generated in the population.

Source: own work.

5. VERIFICATION OF THE METHOD FOR MINIMIZING THE RISK OF ACCIDENTS ON THE AIRPORT APRON

5.1. DETERMINATION OF PROBABILITY DISTRIBUTIONS OF AIRPORT APRON SECTIONS OCCUPANCY

The location of sections of the airport apron characterized by a high frequency of ground service vehicle occupancy and the location of aircraft parking spaces are shown in Fig. 2. The accepted risk of an accident (section occupancy) throughout the entire aircraft route was set at 0.46.

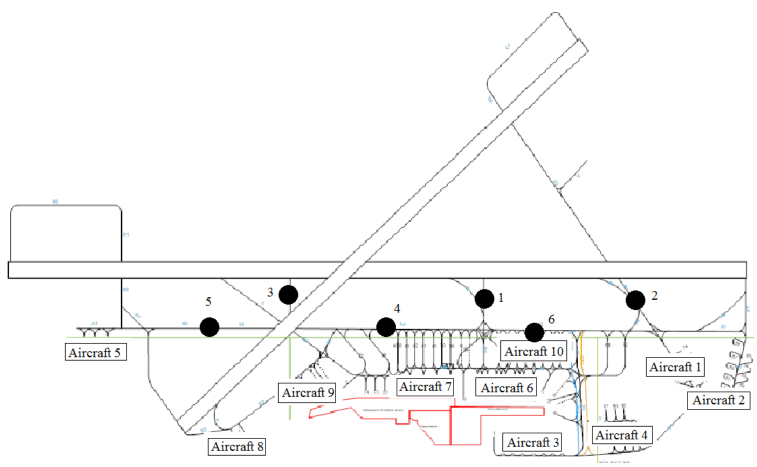

Fig. 2. Location of parking places and section occupancy
Source: own work.

The process of servicing ten aircraft by ground service vehicles was modeled in the GlobSIM simulator. To generate the moments of occupancy of sections of the airport apron by these vehicles, a simulation of the routes of vehicles to aircraft parking spaces at given times of arrival or departure of aircraft was carried out. As a result of the simulation, six sections were generated on the airport apron with the highest frequency of ground service vehicles. Theoretical probability distributions of the occupation of these sections by ground service vehicles were determined for these sections. The times when these points are occupied are presented in Table 5.1. The times of arrival or departure of aircraft are presented in Table 5.2. The probability on other sections was assumed to be 0.1.

Table 5.1. Moments of occupancy of airport apron sections

Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
8:03	8:01	8:08	8:00	8:00	8:04
8:05	8:04	8:10	8:02	8:03	8:10
8:12	8:06	8:15	8:07	8:05	8:13
8:16	8:10	8:19	8:12	8:10	8:17
8:19	9:11	8:22	8:15	8:13	8:22
8:24	8:15	8:26	8:18	8:15	8:23
8:27	8:17	8:28	8:20	8:17	8:27
8:29	8:22	8:30	8:22	8:20	8:29
8:30	8:25	8:33	8:24	8:23	8:33
8:33	8:29	8:34	8:29	8:25	8:34
8:35	8:30	8:37	8:30	8:27	8:39
6:38	8:32	8:40	8:31	8:30	8:44
8:42	8:40	8:42	8:40	8:36	8:45
8:46	8:41	8:45	8:41	8:40	8:47

Source: own work.

Table 5.2. Aircraft arrival and departure times

Number	Arrival time	Departure time	Number	Arrival time	Departure time
		8:30			-
Aircraft 1	-	9:00	Aircraft 6	8:15	9:15
Aircraft 2	-	9:10	Aircraft 7	-	9:25
Aircraft 3	-	-	Aircraft 8	-	-
Aircraft 4	9:20	-	Aircraft 9	9:25	-
Aircraft 5	9:35		Aircraft 10	9:40	

Source: own work.

The Chi-square test was used to determine the theoretical distributions on individual sections of the airport apron, which is dedicated to defining normal and close-to-normal distributions. The tested samples are small, so in addition to the Chi-square test, the Kolmogorov-Smirnov test was also used. The use of the Kolmogorov-Smirnov test is only an additional activity supporting the final decision regarding the type of decomposition. The tests were carried out for a significance level of $\alpha = 0.05$. The test results are presented in Table 5.3.

 DOI: 10.55676/asi.v4i2.92

Table 5.3. Concordance tests and distribution parameters for the section occupancy

Measurement points	Statistic	Chi-square test probability	Statistic	K-S test probability	Parameters of distribution	Distribution
1	3.36631	0.84993	0.04411	-	μ = 852; s^2 = 54382	normal
2	2.02111	0.30016	0.03721	-	θ = 12.42; k = 41.67	gamma
3	2.11406	0.47930	0.03901	-	θ = 14.13; k = 35.01	gamma
4	5.21349	0.69781	0.05570	-	μ = 834.9; s^2 = 54756	normal
5	0.87713	0.83637	0.03451	-	θ = 27.755; k = 21.5	gamma
6	7.14341	0.82282	0.06511	-	μ = 834,9; s^2 = 53716	normal

Source: own work.

5.2. CALIBRATION AND VERIFICATION OF THE ANT ALGORITHM

The following α parameter values were adopted for testing the ant algorithm: 1; 3; 5; 10; 20, parameter β: 0.5; 1; 5 and parameter ρ: 0.2; 0.4; 0.6; 0.8. The adopted values include standard values for the ant algorithm, e.g. α = 1, β = 0.5, ρ = 0.5 and values adopted to test the algorithm's behaviour in the examined problem. For this number of specific parameters, 60 possible test settings were created, i.e.: (5 (α parameter) x 3 (β parameter) x 4 (ρ parameter) = 60). The test combinations are presented in Table 5.4. Table 5.5 summarises the results, which shows the value of pheromone in the ant's route.

Table 5.4. Test settings of the ant algorithm parameters

Test	α	β	ρ	Test	α	β	ρ	Test	α	β	ρ
1	1	0.5	0.2	21	1	1	0.2	41	1	5	0.2
2	1	0.5	0.4	22	1	1	0.4	42	1	5	0.4
3	1	0.5	0.6	23	1	1	0.6	43	1	5	0.6
4	1	0.5	0.8	24	1	1	0.8	44	1	5	0.8
5	3	0.5	0.2	25	3	1	0.2	45	3	5	0.2
6	3	0.5	0.4	26	3	1	0.4	46	3	5	0.4
7	3	0.5	0.6	27	3	1	0.6	47	3	5	0.6
8	3	0.5	0,8	28	3	1	0.8	48	3	5	0.8
9	5	0.5	0.2	29	5	1	0.2	49	5	5	0.2
10	5	0.5	0.4	30	5	1	0.4	50	5	5	0.4
11	5	0.5	0.6	31	5	1	0.6	51	5	5	0.6
12	5	0.5	0.8	32	5	1	0.8	52	5	5	0.8
13	10	0.5	0.2	33	10	1	0.2	53	10	5	0.2
14	10	0.5	0.4	34	10	1	0.4	54	10	5	0.4
15	10	0.5	0.6	35	10	1	0.6	55	10	5	0.6
16	10	0.5	0.8	36	10	1	0.8	56	10	5	0.8
17	20	0.5	0.2	37	20	1	0.2	57	20	5	0.2
18	20	0.5	0.4	38	20	1	0.4	58	20	5	0.4
19	20	0.5	0.6	39	20	1	0.6	59	20	5	0.6
20	20	0.5	0.8	40	20	1	0.8	60	20	5	0.8

Source: own work.

Table 5.5. Summary of the results of the ant algorithm

Test	pheromone	Test	pheromone	Test	pheromone
1	39111	21	39800	41	39345
2	39213	22	39899	42	39532
3	39235	23	39700	43	39734
4	39177	24	39701	44	39777
5	39780	25	39623	45	39811
6	39631	26	39777	46	39000
7	39811	27	39812	47	39611
8	39444	28	39531	48	39022
9	39122	29	39123	49	39233
10	39789	30	39888	50	39111
11	38934	31	38145	51	38112
12	38012	32	38222	52	38452
13	38977	33	38903	53	38924
14	38993	34	38091	54	38915
15	39222	35	38000	55	38453
16	38111	36	38731	56	38123
17	38230	37	38111	57	38743
18	38444	38	38001	58	38432
19	38112	39	38111	59	38112
20	38903	40	38301	60	38463

Source: own work.

Experimentally, the number of algorithm iterations was 200 repetitions, and the population size was 50 ants. The ant algorithm was implemented in the C# programming language Table 5.5 shows that the highest pheromone value is 39899 for test number 22 with algorithm parameters $\alpha = 1, \beta = 1, \rho = 0.4$. The pheromone value was generated based on determining the minimum probability of the aircraft route being occupied by ground service vehicles. The route occupancy probabilities for each aircraft are as follows: the aircraft 1: P1 = 0.33; the aircraft 2: P2 = 0.30; the aircraft 3: P3 = 0.38; the aircraft 4: P4 = 0.40; the aircraft 5: P5 = 0.39; the aircraft 6: P6 = 0.41; the aircraft 7: P7 = 0.35; the aircraft 8: P8 = 0.32; the aircraft 9: P9 = 0.30; the aircraft 10: P10 = 0.31. The average time for generating a single solution by the algorithm is 4 minutes. Examples of driving routes for aircraft 3 and 4 are shown in Fig. 3.

The algorithm verification process was carried out based on generating 100 solutions (aircraft driving routes) and then checking the correctness of the generated routes. The algorithm parameters in the verification process were set by test 22.

 DOI: 10.55676/asi.v4i2.92

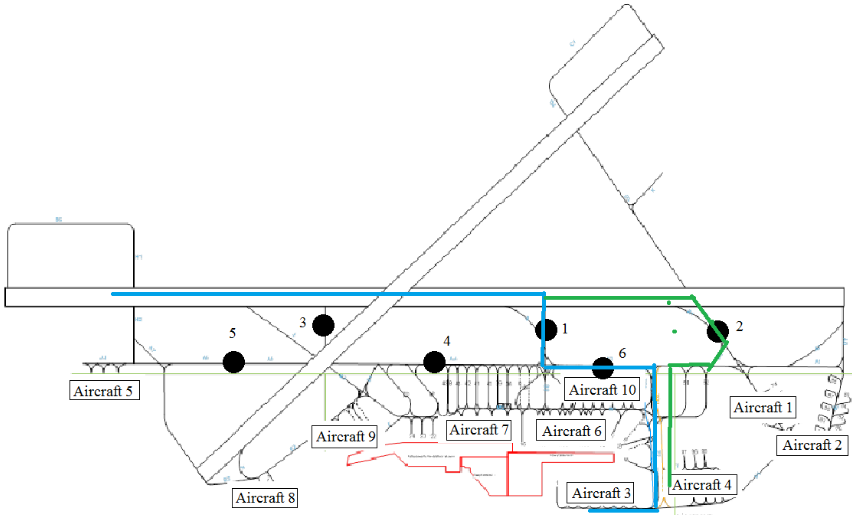

Fig. 3. Aircraft routes

Source: own work.

The incorrect route is when the aircraft will appear when ground service vehicles occupy the given section (Table 5.1). The ant algorithm is probabilistic, so each time it is run, it can generate different solutions and thus achieve different local optima. Based on Table 5.6, the effectiveness of the ant algorithm and the developed method was 90%.

Table 5.6. Efficiency of the ant algorithm (PH – pheromone, E – efficiency)

Test	PH	E	Test	PH	E	Test	PH	E	Test	PH	E	Test	PH	E
1	39819	Yes	21	39711	No	41	39319	Yes	61	39453	Yes	81	39453	Yes
2	39511	No	22	39732	Yes	42	39820	Yes	62	39444	Yes	82	39876	Yes
3	39313	Yes	23	39411	Yes	43	39319	Yes	63	39032	Yes	83	39819	Yes
4	39811	Yes	24	39712	Yes	44	39112	Yes	64	39612	Yes	84	39188	Yes
5	39819	Yes	25	39820	Yes	45	39711	Yes	65	39820	Yes	85	39675	Yes
6	39234	Yes	26	39776	Yes	46	39811	Yes	66	39112	Yes	86	39678	Yes
7	39555	Yes	27	39457	Yes	47	39719	Yes	67	39732	Yes	87	39820	Yes
8	39453	Yes	28	39457	Yes	48	39829	Yes	68	39345	Yes	88	39722	Yes
9	39820	Yes	29	39711	Yes	49	39311	Yes	69	39819	Yes	89	39711	Yes
10	39123	Yes	30	39909	Yes	50	39819	Yes	70	39111	Yes	90	39623	Yes
11	39646	No	31	39777	Yes	51	39212	Yes	71	39638	Yes	91	39763	Yes
12	39234	Yes	32	39453	Yes	52	39819	No	72	39321	No	92	39453	Yes
13	39711	Yes	33	39123	Yes	53	39820	Yes	73	39820	Yes	93	39819	Yes
14	39456	Yes	34	39819	Yes	54	39314	Yes	74	39111	Yes	94	39473	No
15	39453	Yes	35	39472	Yes	55	39834	Yes	75	39463	Yes	95	39222	No
16	39222	Yes	36	39111	No	56	39319	Yes	76	38261	Yes	96	39453	Yes
17	39211	Yes	37	39712	Yes	57	39811	Yes	77	39123	Yes	97	39445	Yes
18	39711	Yes	38	39463	Yes	58	39519	Yes	78	39377	Yes	98	39711	Yes
19	39876	No	39	38643	Yes	59	39014	No	79	39465	Yes	99	39125	Yes
20	39111	Yes	40	39711	Yes	60	39811	Yes	80	39574	Yes	100	39453	Yes

Source: own work.

6. CONCLUSIONS

The research aimed to develop a method to minimize the risk of accidents in in-ground airport operations carried out by aircraft. The developed method is based on the ant algorithm. Considering the results generated by the ant algorithm, the appropriate setting of the algorithm's input parameters is essential in determining the solution. Finding the right balance between the influence of pheromone (α parameter) and heuristic information (β) is crucial in calibrating the algorithm. The results of the algorithm depend on the settings of these input parameters. In the research presented in this paper, a limited number of parameter settings were examined, which narrows the scope for searching for a minimal solution. On this basis, it can be concluded that the result generated by the ant algorithm is suboptimal.

The verification of the method confirmed its high effectiveness of 90% of correctly generated solutions. The developed method can manage traffic safety on the airport apron.

For further research, other optimization algorithms described in the literature should be used, e.g. the genetic algorithm and their effectiveness in the examined problem should be checked. The results encourage the continuation of research by introducing stochastic parameters, e.g., driving times.

The problem of minimizing the risk of accidents in-ground airport operations was presented using a single-criteria approach. Further research will be aimed at introducing additional criteria, e.g. time of airport apron occupancy by aircraft and offering this problem in a multi-criteria approach.

BIBLIOGRAPHY

Agustín A., Alonso-Ayuso A., Escudero L.F., Pizarro C., On air traffic flow management with rerouting, "Eur. J. Oper. Res." 2012, vol. 219, no. 1, pp. 167–177.

Andreatta G., Brunetta L., Multiairport Ground Holding Problem: A Computational Evaluation of Exact Algorithms, "Operations Research" 1998 , vol. 46(1), pp. 57–64.

Andreatta G., Romanin-Jacur G., Aircraft Flow Management under Congestion, "Transp. Sci." 1987, vol. 21, no. 4, pp. 249–253.

Ball M.O., Hoffman R., Odoni A.R., Rifkin R., A Stochastic Integer Program with Dual Network Structure and Its Application to the Ground-Holding Problem, "Oper. Res." 2003, vol. 51, no. 1, pp. 167–171.

Beasley J.E., Krishnamoorthy M., Sharaiha Y.M., Abramson D., Scheduling Aircraft Landings – The Static Case, "Transportation Science" 2000, vol. 34, no. 2, pp. 180–197.

Bennell J.A., Mesgarpour M., Potts C.N., Airport runway scheduling, "Ann Oper Res" 2013, vol. 204, no. 1, pp. 249–270.

Bihar R.A., A conceptual solution to the aircraft gate assignment problem using 0, 1 linear programming, "Computers & Industrial Engineering" 1990, vol. 19, no. 1, pp. 280–284.

 DOI: 10.55676/asi.v4i2.92

Certificate granted to the software by the Civil Aviation Office on September 17, 2018 No. PL/FISP-TO/PWBISEK.

Cur K., Zieja M., Czerwiński T., Tomaszewska J., Comparison of readiness to perform the task of aircraft used for cadet training, Proceedings of the 31st European Safety and Reliability Conference, ESREL 2021, https://doi.org/10.3390/aerospace9010014, pp. 337–343.

Čokorilo O., Human factor modelling for fast-time simulations in aviation, "Aircr. Eng. Aerosp. Technol. Int. J." 2013, vol. 85, no. 5, pp. 389–405.

D'Ariano A., Pacciarelli D., Pistelli M., Pranzo M., Real-time scheduling of aircraft arrivals and departures in a terminal maneuvering area, "Networks" 2015, vol. 65, no. 3, pp. 212–227.

Dorigo M., Gambardela L.M., Ant Colonies for the Travelling Salesman Problem, "BioSystems" 1997, vol. 43, pp. 73–81.

Dorigo M., Gambardela L.M., Ant Colony System: A cooperative learning approach to the traveling salesman problem, "IEEE Transactions on Evolutionary Computation" 1997, vol. 1(1), pp. 53–66.

Dorigo M., Stutzle T., Ant Colony Optimization, Bradford Books 2004.

Fahle T., Feldmann R., Götz S., Grothklags S., Monien B., The Aircraft Sequencing Problem, [in:] Computer Science in Perspective, Springer 2023, vol. 2598, pp. 152–166.

Fiuk J., Chamier-Gliszczynski N., Jacyna M., Izdebski M., Energy Efficiency of Transport Tasks Performed by the Air SAR System in the Baltic Sea: Case Study, "Energies" 2022, vol. 15(2), pp. 643.

Girish B.S., An efficient hybrid particle swarm optimization algorithm in a rolling horizon framework for the aircraft landing problem, "Applied Soft Computing" 2016, vol. 44, pp. 200–221.

Gołda P., Zawisza T., Izdebski M., Evaluation of efficiency and reliability of airport processes using simulation tools, "Eksploatacja i Niezawodność" 2021, vol. 23, no. 4, pp. 659–669.

Izdebski M., Gołda P., Zawisza T., The Use of Simulation Tools to Minimize the Risk of Dangerous Events on the Airport Apron, [in:] Advanced Solutions and Practical Applications in Road Traffic Engineering: conference proceedings, ed. E. Macioszek, A. Granà, G. Sierpiński, Lecture Notes in Networks and Systems, 2023, vol. 604, Springer, https://doi.org/10.1007/978-3-031-22359-4_6, pp. 91–107.

Izdebski M., Gołda P., Zawisza T., The use of the ant algorithm in the model of safety management of the traffic organization at the apron, "Journal of KONBiN" 2022, vol. 52, no. 2, pp. 63–76.

Izdebski M., Jacyna M., An Efficient Hybrid Algorithm for Energy Expenditure Estimation for Electric Vehicles in Urban Service Enterprises, "Energies" 2021, vol. 14, no. 7, pp. 1–23.

Liu P.B., Hansen M., Mukherjee A., Scenario-based air traffic flow management: From theory to practice, "Transp. Res. Part B Methodol." 2008, vol. 42, no. 7, pp. 685–702.

Mascio P.D., Rappoli G., Moretti L., Analytical Method for Calculating Sustainable Airport Capacity, "Sustainability" 2020, vol. 12, no. 21.

Ng K.K.H., Lee C.K.M., Chan F.T.S., Lv Y., Review on meta-heuristics approaches for airside operation research, "Applied Soft Computing" 2018, vol. 66, pp. 104–133.

Ntakolia C., Lyridis D.V., A n − D ant colony optimization with fuzzy logic for air traffic flow management, "Oper. Res." 2022, no. 22, pp. 5035–5053.

Samà M., D'Ariano A., Corman F., Pacciarelli D., Coordination of scheduling decisions in the management of airport airspace and taxiway operations, "Transportation Research Part A: Policy and Practice" 2018, vol. 114, pp. 398–411.

Samà M., D'Ariano A., D'Ariano P., Pacciarelli D., Optimal aircraft scheduling and routing at a terminal control area during disturbances, "Transportation Research Part C: Emerging Technologies" 2014, vol. 47, pp. 61–85.

Terrab M., Odoni A.R., Strategic Flow Management for Air Traffic Control, "Oper. Res." 1993, vol. 41, no. 1, pp. 138–152.

 DOI: 10.55676/asi.v4i2.92