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THE USE OF THE ANT ALGORITHM IN THE MODEL OF SAFETY MANAGEMENT OF THE TRAFFIC ORGANIZATION AT THE APRON

Wykorzystanie algorytmu mrówkowego w modelu zarządzania bezpieczeństwem organizacji ruchu na płycie lotniska

Abstract: *In the article, traffic safety management on the apron comes down to determining appropriate routes for ground handling vehicles to avoid collision situations with aircraft. The route search problem is a decision problem, so different optimization algorithms are used to solve it. Bearing in mind the growing importance of heuristic algorithms in the effectiveness of solving complex decision problems, the authors of this study analyzed the possibility of using the ant algorithm to determine the driving routes of ground service vehicles. As part of the research, the decision model of traffic safety management on the apron was presented.*
Keywords: ant algorithm, safety management, airport traffic organization

Streszczenie: *W artykule zarządzanie bezpieczeństwem ruchu na płycie lotniska sprowadza się do wyznaczenia odpowiednich tras jazdy pojazdów obsługi naziemnej w celu uniknięcia sytuacji kolizyjnych ze statkami powietrznymi. Problem wyszukiwania tras jest problemem decyzyjnym, więc w celu jego rozwiązania stosowane są różne algorytmy optymalizacyjne. Mając na uwadze rosnące znaczenie algorytmów heurystycznych w efektywności rozwiązywania złożonych problemów decyzyjnych, autorzy niniejszego opracowania przeanalizowali możliwość zastosowania do wyznaczenia tras jazdy pojazdów obsługi naziemnej algorytmu mrówkowego. W ramach realizacji badań przedstawiono model decyzyjny zarządzania bezpieczeństwem ruchu na płycie lotniska.*
Słowa kluczowe: algorytm mrówkowy, zarządzanie bezpieczeństwem, organizacja ruchu na płycie lotniska

1. Introduction

Traffic safety is a key and essential factor that must be met when performing all airport operations on the apron [10, 20]. In heavy traffic at the airport, there are conflict situations that result in delays in the take-off or landing of planes. The occurrence of delays generates additional costs and disrupts the traffic at the airport. From the point of view of the proper operation of the airport, it is essential to minimize any disruptions affecting aircraft take-off and landing delays.

The primary operations that determine the capacity of airports are take-off and landing operations on the runway [1, 2], or the allocation of gates and parking stands [7]. The issue of aircraft movement on the tarmac is a set of problems in scheduling and finding the most advantageous route. It is about driving the aircraft on the ground roads at the airport so that they can achieve their goals within a certain time, i.e., reduce the total travel time and fit into time windows to maintain the necessary time separations. Determining aircraft driving routes on the apron is a subject widely described in the literature [12, 9, 17]. The paper [14] emphasizes that the operation of taxiing aircraft on the apron is the most critical element affecting the safety and capacity of an airport.

To a large extent, airport safety management depends on determining the driving routes of individual road users. The route search problem is a decision problem, so different optimization algorithms are used to solve it. Search algorithms in the shortest path graph are the basis for solving most problems in the field of operations research [8]. Bearing in mind that the elements of the airport apron with their connections can be presented graphically using a graph, the search algorithms in the shortest path graph are successfully used to determine the paths of ships on the apron. The main shortest path search algorithms are Dijkstra [6], Ford-Bellman, A* [5], Floyd-Warshall, and Johnson.

Solutions using a genetic algorithm are time-effective and therefore suitable for practical use. The genetic algorithms used in determining taxi routes have been widely described in publications [11, 3].

The problems of airport traffic management are complex optimization problems. The functions of the criterion minimize the total taxiing time of the aircraft [15, 18] or the separation times between successive ships [4].

In the article, traffic safety management on the apron comes down to determining appropriate routes for ground handling vehicles to avoid collision situations with aircraft. Hazardous situations involving aircraft and ground handling vehicles are defined as situations that cause an aircraft to stop, change its taxi route, or otherwise delay the take-off or landing of an aircraft at an airport apron. Dangerous situations have been described by theoretical probability distributions of a given section being occupied by aircraft. The random variable determining the probability distribution of a given apron section being occupied by aircraft has the interpretation of the time (hour) of the aircraft's arrival on a given section of the route. Determining the probability of occurrence of hazardous events on the apron plays an important role in the safety management process. The paths of ground handling vehicles have been designed in such a way as to minimize the probability of hazardous incidents involving aircraft (e.g. collisions, bumps). There is a need to develop an approach that allows for flexible and efficient routing of ground handling vehicles. Bearing in mind the growing importance of heuristic algorithms in the effectiveness of solving complex decision problems, the authors of this study analyzed the possibility of using the ant algorithm to determine the driving routes of ground service vehicles. This algorithm is often used to determine vehicle driving routes [19, 16, 13].

As part of the research, the decision model of traffic safety management on the apron was presented, i.e. the criterion's decision variables, limitations, and functions were determined.

In the summary of the literature analysis, it can be stated that most of the publications on airport safety management refer to the determination of aircraft driving routes. Designating the movement of ground handling vehicles is a new approach in airport safety management.

2. Decision-making model of safety management of airport traffic organization

The developed apron safety management model relates to the situation in which the departure and arrival times of the aircraft included in the arrival/departure schedules are known. To construct the decision model, the following assumptions were made:

- Apron safety management is considered about the routing of vehicles.
- The random variable that determines the probability distribution of the occupation of a given apron section by aircraft interprets the time (hour) of the aircraft's arrival on a given section of the route. Therefore, the ground handling vehicle must arrive on a given route segment at such a time that the probability that the route segment is occupied by the aircraft is minimal.
- To simplify the model, it has been assumed that the aircraft arrival time is interpreted as the aircraft's arrival time at the apron stand and the time of departure as the time of departure from the ship's parking place.
- Theoretical probability distributions of the occupancy of sections on the apron by aircraft are known.
- The aircraft's operational characteristics on the tarmac are not known, i.e. their speed and route are not known. Determining the course of aircraft paths on the apron depends on many random factors, e.g. weather conditions; hence the traffic characteristics of ships were determined by the probability of the occupancy of a given section of the apron by aircraft.
- The road handling characteristics of the ground handling vehicles are determined based on the proposed decision model.
- The staging points of individual ground handling vehicles and aircraft on the apron are known.

The inputs to the decision model are defined in the tabs. 1 and 2.

Table 1

Collective list of airport apron structure elements

Parameter	Explanation
PP	set of numbers for ground handling vehicles staging points
I	set of intermediate point numbers
PS	set of numbers of aircraft parking points (servicing)
LPPI	set of connections between a vehicle parking point and an intermediate point
LII	set of links between intermediate points
LIPS	set of connections between an intermediate and an aircraft parking point
LPSI	set of connections between an aircraft parking and an intermediate point
LIPP	set of connections between an intermediate point and the staging point

Table 2

Collective list of point and linear characteristics of the airport apron

Parameter	Explanation
TO	aircraft maintenance time matrix for ground handling vehicles
TD	matrix of delays at intermediate points
LP	matrix of the number of vehicles of a certain type at a given stopping point
TL	matrix for the time of arrival of aircraft to a standpoint
TS	matrix of aircraft standby take-off times
D1	distance between the vehicle staging point and an intermediate point
D2	distance between intermediate points
D3	distance between an intermediate point and an aircraft stand (servicing) point
D4	distance between an aircraft parking point and an intermediate point
D5	distance between an intermediate point and a staging point of vehicles
PE	probability of the section being occupied

The decision variables of the model are presented in tab. 3.

Table 3

Collective list of decision variables

Parameter	Explanation
H	a moment of departure of a vehicle of a given type from a parking point to a specific aircraft located at a given point of the airport apron in a given task
X	a departure of the vehicles of a given type from a specified stopping point
V1	speed between the staging point of vehicles and the intermediate point
V2	a vehicle speed between intermediate points
V3	speed of vehicles between an intermediate point and an aircraft parking point
V4	speed of vehicles between an aircraft parking point and an intermediate point
V5	speed between the intermediate point and the staging point of the vehicles
X1	a connection between the staging point of vehicles and the intermediate point
X2	a connection between intermediate points
X3	a connection between an intermediate point and an aircraft parking point
X4	a connection between an aircraft parking point and an intermediate point
X5	a connection between the intermediate and the staging point of the vehicles

Given the complexity of the mathematical model, only exemplary constraints have been selected. The model constraints take the following form:

– The number of ground handling vehicles at a given apron standstill is to be maintained:

$$\forall r \in \boldsymbol{R}, \forall pp \in \boldsymbol{PP} \quad \sum_{poj \in \boldsymbol{POJ}} x^{poj,r,pp} \leq lp^{r,pp} \tag{1}$$

– The maintenance of the aircraft by vehicles is to take place within the specified time windows of the ship's arrival (2) and take-off (3):

$\forall\, poj \in \boldsymbol{POJ}$, $\forall\, r \in \boldsymbol{R}$, $\forall\, pp \in \boldsymbol{PP}$, $\forall\, s \in \boldsymbol{S}$, $\forall\, ps \in \boldsymbol{PS}$, $\forall\, z \in \boldsymbol{Z}$, $\forall (w,w') \in \boldsymbol{LPPI}$, $\forall\, (w,w') \in \boldsymbol{LIPS}$

$$h^{poj,r,pp,s,ps,z} + x1^{(w,w'),poj,r,z} \cdot \frac{d1^{(w,w')}}{v1^{(w,w'),poj,r,z}} + \sum_{(w,w') \in \boldsymbol{LII}} x2^{(w,w'),poj,r,z} \cdot \frac{d2^{(w,w')}}{v2^{(w,w'),poj,r,z}} +$$

$$+x3^{(w,w'),poj,r,z} \cdot \frac{d3^{(w,w')}}{v3^{(w,w'),poj,r,z}} \geq tl^{s,ps} - \Delta t \tag{2}$$

$$h^{poj,r,pp,s,ps,z} + x1^{(w,w'),poj,r,z} \cdot \left(\frac{d1^{(w,w')}}{v1^{(w,w'),poj,r,z}} + td^{w',poj,r,z}\right) + \sum_{(w,w')\in \boldsymbol{LII}} x2^{(w,w'),poj,r,z} \cdot$$

$$\cdot \left(\frac{d2^{(w,w')}}{v2^{(w,w'),poj,r,z}} + td^{w',poj,r,z}\right) + x3^{(w,w'),poj,r,z} \cdot \left(\frac{d3^{(w,w')}}{v3^{(w,w'),poj,r,z}} + to^{s,r}\right) \geq ts^{s,ps} - \Delta t \tag{3}$$

- The travel time of the ground handling vehicle to the aircraft service points must not be exceeded (T - acceptable travel time) in the case of arrival (4), take-off (5):

∀ poj∈**POJ**, ∀ r∈**R**, ∀ pp∈**PP**, ∀ s∈**S**, ∀ ps∈**PS**, ∀ z∈**Z**, ∀(w,w')∈**LPPI**, ∀ (w,w')∈**LIPS**

$$x1^{(w,w'),poj,r,z} \cdot \frac{d1^{(w,w')}}{v1^{(w,w'),poj,r,z}} + \sum_{(w,w')\in \boldsymbol{LII}} x2^{(w,w'),poj,r,z} \cdot \frac{d2^{(w,w')}}{v2^{(w,w'),poj,r,z}} +$$

$$+x3^{(w,w'),poj,r,z} \cdot \frac{d3^{(w,w')}}{v3^{(w,w'),poj,r,z}} \leq T \tag{4}$$

$$x1^{(w,w'),poj,r,z} \cdot \left(\frac{d1^{(w,w')}}{v1^{(w,w'),poj,r,z}} + td^{w',poj,r,z}\right) + \sum_{(w,w')\in \boldsymbol{LII}} x2^{(w,w'),poj,r,z} \cdot$$

$$\left(\frac{d2^{(w,w')}}{v2^{(w,w'),poj,r,z}} + td^{w',poj,r,z}\right) + x3^{(w,w'),poj,r,z} \cdot \frac{d3^{(w,w')}}{v3^{(w,w'),poj,r,z}} \leq T \tag{5}$$

- It is not possible for two ground handling vehicles to arrive at an intermediate point (in the case of aircraft arrival):

∀ *poj,poj'*∈***POJ*** (*poj≠poj'*), ∀ *r,r'*∈***R*** (*r≠r'*), ∀ *pp*∈***PP***, ∀ *s*∈***S***, ∀ *ps*∈***PS***, ∀ *z,z'*∈***Z*** (*z≠z'*), ∀(*w,w'*)∈***LPPI***

$$h^{poj,r,pp,s,ps,z} + x1^{(w,w'),poj,r,z} \cdot \frac{d1^{(w,w')}}{v1^{(w,w'),poj,r,z}} \neq h^{poj',r',pp,s,ps,z'} + x1^{(w,w'),poj',r',z'} \cdot \frac{d1^{(w,w')}}{v1^{(w,w'),poj',r',z'}} \tag{6}$$

The probability function of occupancy by aircraft of the entire route performed by individual vehicles was presented as (it was assumed that the model tests the probability of occupation between intermediate points):

∀ poj∈**POJ**, ∀ r∈**R**, ∀ z∈**Z**

$$F(\text{X2}) = \prod_{(w,w')\in \boldsymbol{LII}} x2^{(w,w'),poj,r,z} \cdot p\left(E^{(w,w')}\right) \longrightarrow \min \tag{7}$$

3. The ant algorithm

The ants from the population determine the driving routes of the individual ground handling vehicles. To determine the decision variables described in the mathematical model in chapter two, the ant route will consist of points defining the hours of departure of the ant from the loading point, which is interpreted as the time of departure of the vehicle from the loading point (determination of the decision variable H) - layer III, from the points determining driving route - layer V (decision variables X1-X5), points determining the assignment of a given vehicle to the task - layer - II (decision variable X), points determining the speed on each section of the route - layer IV (decision variable V1-V5), points determining a location of the base from which the vehicle will be selected - layer I and aircraft staging points - layer VI. Graphical elements of a fragment of the ant's route on the relation between vehicle stopping point and aircraft service point are shown in fig. 1.

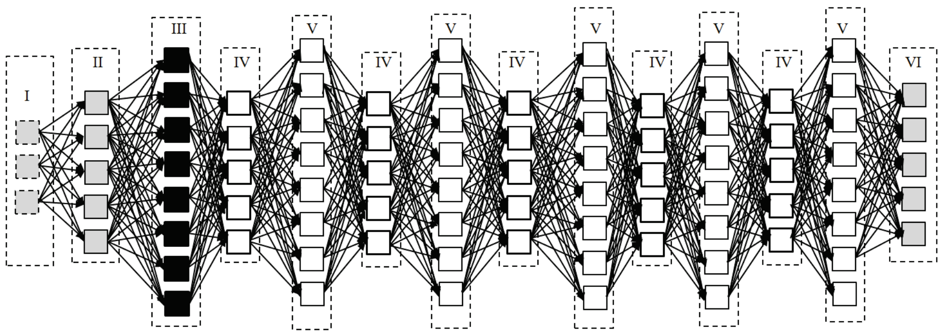

Fig. 1. An ant route

The ant starts the route by choosing a parking place for the vehicles. In the following steps, the ant moves through the various points of the route until it reaches the aircraft service point. The ant's other route, and thus the selection of subsequent route points, takes place with a certain probability (the algorithm assumes that the ant selects only those route points that do not cause the ant to move away from the endpoint):

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

where:

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

$\eta_{yz}(t)$ – heuristic information:

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

where:

$p(y,z)$ – the probability of the section being occupied, (in order to determine the function of the criterion (7)), the probability depends on the moment of arrival of the ant on a given section of the route,

α, β – effects of pheromones and heuristic data on ant behavior,

Ω^{mr} – set of all point elements of the transportation network, l – potential ant route points taken into account at the moment of choosing the next ant route point.

After all the ants have finished building routes, the pheromone trace is updated. In the beginning, it is assumed that the path on the connections between route points is equally vital. In subsequent iterations, the pheromone trace is calculated according to the formula:

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

where:

mr – another ant in the anthill $mr \in \boldsymbol{MR}$,

ρ – pheromone volatilization rate $(0<\rho\leq 1)$,

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

The first component of the formula (10) determines the pheromone volatilization rate, while the second determines the pheromone amplification and takes the value:

$$\Delta\tau_{yz}^{mr}(t) = \begin{cases} \dfrac{1}{P^{mr}(t)} - K^{mr}(t) & \text{when the route } (y,z) \text{ was used by the ant } mr; \\ 0 & \text{otherwise } 0; \end{cases} \tag{11}$$

where:

$P^{mr}(t)$ – the probability of the entire route being occupied;

$K^{mr}(t)$ – penalty for exceeding any limit from the decision model.

The ant algorithm is iterative; its solution is improved in the next iteration. The algorithm runs until the stop condition is reached. The condition for the stop is a fixed number of iterations. The number of ants in the population creating individual routes (solutions) and the number of iterations are determined at the beginning of the implementation of the algorithm. The steps of the algorithm can be represented as follows:

- Step 1. Identification of the main route points for individual ground handling vehicles. Ground handling vehicles' travel routes depending on the type of service, e.g. refuelling or loading an aircraft, and on the phase of flight, e.g. take-off or landing of a ship. In the case of aircraft refuelling, both in the take-off and landing phase, the route consists of the following points: base - ship's berth - base. For ship landing and unloading operations, the route consists of the following points: base - terminal - base. In the case of a ship taking off from a point located on the airport apron, the route consists of the following points: base - tarmac stop - base. The task of the ant algorithm is to calculate routes between the route mentioned above points.
- Step 2. Designating a route for each ant in a population.
- Step 3. Pheromone update.
- Step 4. The steps of the algorithm 2-3 are repeated with a certain number of iterations.
- Step 5. Selection of the route with the maximum pheromone value from the population. This route is the end of the algorithm.

4. Verification of the ant algorithm

The characteristics of the tasks to be performed by individual ground handling vehicles are presented in tab. 4. Aircraft I is in the landing phase. The transport task is to transport the cargo to the terminal. Ship II, III and IV are in the take-off phase. A transport task for ground handling vehicles to deliver fuel to vessels.

Table 4

Characteristics of the tasks

Number of aircraft	Phase	Arrival time	Departure time	Operation
I	landing	8:45	-	unloading
II	start	-	9:35	refueling
III	start	-	11:35	refueling
IV	start	-	11:00	refueling

Figure 2 shows the airport apron infrastructure. On the route sections (14; 19), (6; 15) and (9; 13), after measuring the occupancy of these sections, it was found that the probability of occupancy of these sections was determined from the normal distribution. The remaining sections of the infrastructure network are underused and the occupancy probability of a section was assumed at the level of 0.1. In the case of vessel I, the service vehicle leaves the base, picks up the cargo from the vessel and transports it to the terminal, and then returns to the base. In the case of ships II, III and IV, the vehicles leave the base to the berths and return to the base after refueling.

The ant algorithm was set to 200 iterations, number of ants in the population 50, parameters α=1,β=0.5.

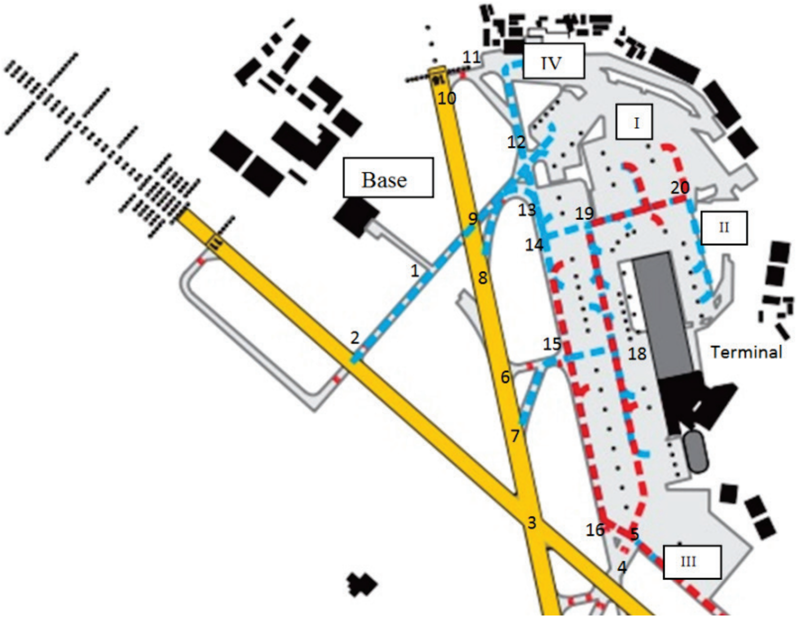

Fig. 2. Airport apron infrastructure

The results of determining the occupancy probability of the entire route for each vehicle in individual iterations are presented in figs. 3-6. An exemplary route for a vehicle serving ship II is (1; 9), (9; 13), (13; 19), (19; 20), (20; 19), (19; 14), (14; 15), (15; 6), (6; 8), (8; 9), (9; 1). The service vehicle left the base for ship II at 9:10. Driving speeds on individual sections (1; 9) = 10 km/h, (9; 13) = 15 km/h, (13; 19) = 15 km/h, (19; 20) = 10 km/h, (20; 19) = 20 km/h, (19; 14) = 10 km/h, (14; 15) = 15 km/h, (15; 6) = 20 km/h, (6; 8) = 10 km/h, (8; 9) = 15 km/h, (9; 1) = 10 km/h. The probability of the occupation of route sections for the vehicle I, P1 = 0.517, the time of determining the solution 55 seconds, the probability of the occupation of the sections of the route for the II vehicle P2 = 0.60, the time of determining the solution 35 seconds, the probability of using the sections of the route for the vehicle III P3 = 0.720, time of determining the solution 40 seconds, probability of the occupation of route sections for the vehicle IV P4 = 0.74, time of determining the solution 34 seconds.

The ant algorithm was compared to Dijkstra's exact algorithm. In the case of vehicle I, Dijkstra's algorithm generated a route with a busy probability P1 = 0.38 in 5 minutes

24 seconds, the difference in the result with the ant algorithm ΔP = 0.137. In the case of vehicle II, Dijkstra's algorithm generated a route with a busy probability P2 = 0.4 in 4 minutes 34 seconds, the difference in the result ΔP = 0.20. In the case of vehicle III, Dijkstra's algorithm generated a route with a busy probability P3 = 0.51 in 5 minutes 14 seconds, the difference in the result ΔP = 0.21. In the case of the IV vehicle, the Dijkstra algorithm generated a route with a busy probability P4 = 0.55 in 3 minutes 24 seconds, the difference in the result ΔP = 0.19.

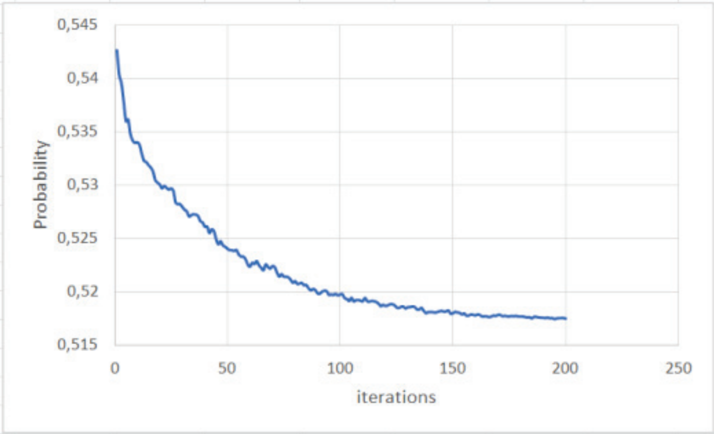

Fig. 3. The probability of taking the route for 1st vehicle

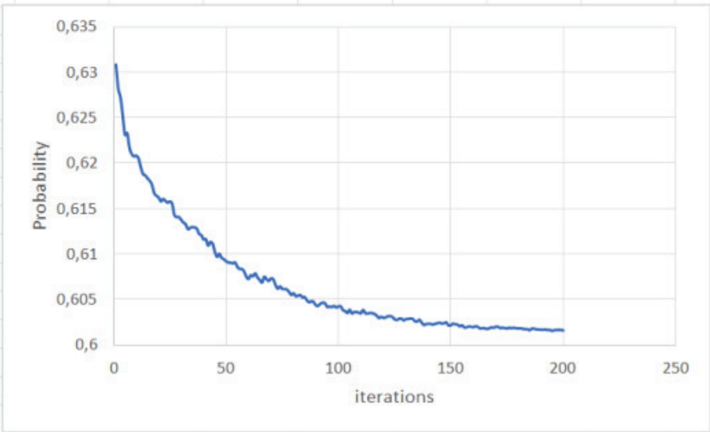

Fig. 4. The probability of taking the route for 2nd vehicle

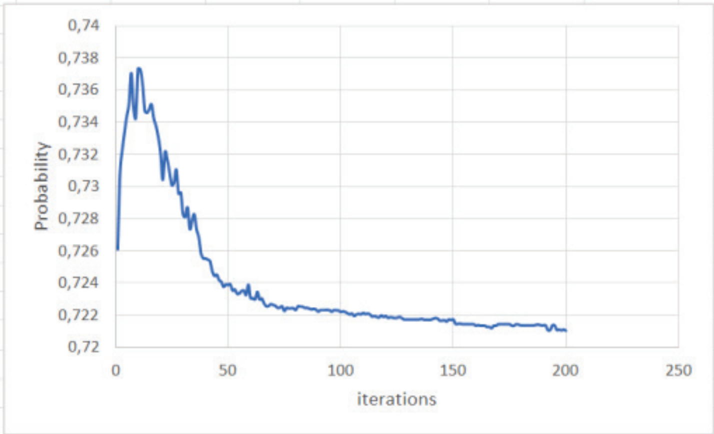

Fig. 5. The probability of taking the route for 3rd vehicle

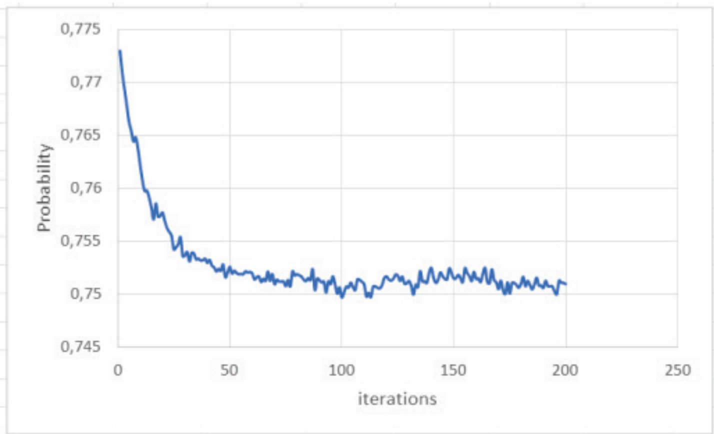

Fig. 6. The probability of taking the for 4th vehicle

5. Conclusions

Managing the safety of airport traffic organization is a complex decision-making problem. At work, the security on the apron depends on the route of the ground handling vehicles. The ant algorithm was used to determine the routes of vehicles carrying out the commissioned tasks. The ant algorithm verification confirmed its effectiveness. The results were compared with Dijkstra's algorithm. The results generated by both algorithms are similar, which proves that the optimization algorithm was correctly selected for the problem under study and that it was perfectly calibrated. It should be emphasized that the ant algorithm belongs to the heuristic algorithms, so it does not guarantee an optimal result, like, for example, Dijkstra. In most cases, it generates a suboptimal solution based on the complexity of decision problems. The time of operation and determination of the solution are of crucial importance in this type of algorithm. The advantage of heuristic algorithms represented by the ant algorithm is the speed of finding a solution. The ant algorithm found a solution in less than one minute in each case. On the other hand, the time of Dijkstra's algorithm was limited to 5 minutes. The local optimum generated by the form algorithm is distant from the global optimum by a value in the range <0.1; 0.21>, which is an acceptable result from a practical point of view.

In the sections of terraces characterized by high traffic, the probabilities of the occupancy of the sections were determined using normal distributions adapted to the existing traffic situation on the airport apron. The probability values at these points on the route depended on when the vehicle appeared on these sections. In the example, these sections were characterized by a high probability of being occupied (above 0.70) in the given periods of ship service, which resulted in an increased likelihood of the occupation of sections along the entire vehicle route. The traffic situation on each section of the route is the main factor influencing the value of the probability of occupancy of this section.

Due to the speed of operation of the proposed method of determining the driving routes of ground handling vehicles, this method can be used to plan the organization of the tasks of ground handling vehicles and thus determine the work schedules of drivers.

6. References

1. Atkin J.A.D., Burke E.K., Greenwood J.S., Reeson D.: Hybrid metaheuristics to aid runway scheduling at London Heathrow airport. Transportation Science, vol. 41, no. 1, 2007.
2. Bianco L., DellOlmo P., Giordani S.: Scheduling models for air traffic control in terminal areas. Journal of Scheduling, vol. 9, 2006.
3. Clare G.L., Richards A.G.: Optimization of Taxiway Routing and Runway Scheduling. IEEE Transactions on Intelligent Transportation Systems, Vol. 12, No. 4, 2011.
4. Clare G.L., Richards A.G.: Optimization of Taxiway Routing and Runway Scheduling. IEEE Transactions on Intelligent Transportation Systems, Vol. 12, No. 4, 2011.
5. Dechter R., Pearl J.: Generalized best-first search strategies and the optimality of A*. Journal of the ACM. 32 (3), 1985.
6. Dijkstry E.W.: A note on two problems in connexion with graphs. In Numerische Mathematik 1, 1959.
7. Dorndorf U., Drexl A., Nikulin Y., Pesch E.: Flight gate scheduling: State-of-the-art and recent developments. Omega, vol. 35, no. 3, 2007.
8. Gallo G., Pallottino S.: Shortest path algorithms. Annals of Operations Research, 13, 1988.

9. Garcia J., Berlanga A., Molina J. M., Casar J. R.: Optimization of airport ground operations integrating genetic and dynamic flow management algorithms. AI Communications, vol. 18, no. 2, 2005.
10. Gołda P., Zawisza T., Izdebski M.: Evaluation of efficiency and reliability of airport processes using simulation tools. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2021; 23 (4).
11. Gotteland J.-B., Durand N.: Genetic algorithms applied to airport ground traffic optimization. Materiał konferencyjne Congress on Evolutionary Computation, Canberra, Australia, vol. 1, 2003.
12. Herrero J.G., Berlanga A., Molina J.M., Casar J. R.: Methods for operations planning in airport decision support systems. Applied Intelligence, vol. 22, no. 3, 2005.
13. Izdebski M., Jacyna M.: An Efficient Hybrid Algorithm for Energy Expenditure Estimation for Electric Vehicles in Urban Service Enterprises. Energies, vol. 14, nr 7, 2021.
14. Liu Y.: Study on optimization for taxiway routing arrangement based on simulation. Applied Mechanics and Materials, Vols. 97-98(2011), 2011.
15. Marin A.: Airport management: Taxi planning. Annals of Operations Research, vol. 143, no. 1, 2006.
16. Montemanni R., Gambardella L.M., Rizzoli A.E., Donati A.V.: Ant Colony System for a Dynamic Vehicle Routing Problem. Journal of Combinatorial Optimization, 10, 2005.
17. Roling P. C., Visser H. G.: Optimal airport surface traffic planning using mixed-integer linear programming. International Journal of Aerospace Engineering, vol. 2008, no. 1, 2008.
18. Ross A., Milutinovi´c D.: An approach to optimization of airport taxiway scheduling and traversal under uncertainty. Journal of Aerospace Engineering, 227(2), IMechE 2012.
19. Yu B., Yang Z.Z.: An ant colony optimization model: The period vehicle routing problem with time windows. Transportation Research Part E, 47, 2011.
20. Żak J., Gołda P., Cur K., Zawisza T.: Assessment of airside aerodrome infrastructure by SAW method with weights from Shannon's interval entropy. Archives of Transport, vol. 60, nr 4, 2021.