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ELEMENTS OF THE MODEL POSITIONING OF AIRCRAFT ON THE APRON

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Abstract:

The design of airports and the organization of their work requires the recognition of the basic components of the air transport process, consisting of an "aerial" part, including the landing phase and the landing operation itself, as well as take-off, the "ground" part, including the task of taxiing aircraft on apron, ground handling tasks, "terminal" part, including passenger handling tasks. These elements form a cause-and-effect sequence, or a series-parallel structure that determines the quality of services provided by the airport, their efficiency, reliability and price. The article presents the issues of decision support for the operation and maintenance of airport infrastructure and traffic management on the ramp and within the airport, i.e. the operation of allocating aircraft to the gates of "gates" using simulation tools. Aircraft taxiing operations on the tarmac integrate the flight phase (along with its components and its problems, such as arriving and departing sequencing) with the ground handling phase of aircraft and passengers at terminals. The model presented in the article is a single element of a holistic approach to the operation of an airport. The overall model consists of the development of decision models for the organization of aircraft traffic on the apron, algorithms for their solution and the possibility of practical application as a simulation tool for analyzing and assessing aircraft traffic processes in the take-off, taxiing and landing phase. To describe the model, a formal mapping of the structure of the necessary airport elements was proposed. A formal record of boundary conditions and criteria relevant to aircraft allocation processes is presented due to the minimization of travel time of passengers transferring between two aircraft assigned to two different gates.

Test results can be used in practice, among others by airspace controllers and airport designers for: analyzing and assessing the possibilities of increasing airport capacity, analyzing and assessing the determination of taxiway lengths, maintaining high safety reserves, etc.

Keywords: *aircraft operation, airport processes, simulation tools, aircraft traffic management, traffic organization on the apron*

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1. Introduction

Most airports are extremely busy environments that operate at their peak. Congestion at airports and in the airspace causes frequent delays that additionally burden already busy schedules. Despite this, as the ICAO mid- and long-term forecasts show, aircraft traffic will increase significantly.

Demand of societies for material goods multiplies the number of flights between countries. Major companies on the world market often have their own aircraft, and the use of aircraft as a means of transport is as common as using a bus or rail. All these elements mean that maintaining high performance of airport processes is a prerequisite for the correct and competitive operation of airports.

Continuous advances in technology stroke these changes, and as a result airports need to implement increasingly new methods and tools to improve their efficiency and effectiveness. Nevertheless, amid the ubiquitous drive to reduce operational and operating costs while increasing airport performance, we must not forget about the safety of work, employees and, most importantly, passengers.

Work safety, apart from efficiency, reliability and the level of generated costs, is one of the basic factors influencing the shape and organization of airport systems. This particularly applies to processes taking place in the area of the airport apron, in which transport processes (usually highly intensified) are carried out in a small space, with a high density of resources and significantly reduced visibility. Therefore, working conditions in the maneuvering area favor hazards associated with collisions or accidents to which not only individuals, but also cargo and infrastructure are exposed.

Despite the interdependence of safety, capacity, weather constraints and individual stakeholder goals, today's air traffic management (ATM) system is already highly optimized. However, there is room for improvement, which requires the ability to recognize and effectively analyze issues such as:

– increasing the airport's capacity,
– planning aircraft positioning on the tarmac,
– taxiway lengths,
– selection of the number of runways,
– optimization of aircraft taxiing routes on the apron,
– take-off and landing order,
– analyze the rapid descent routes,
– maintaining high safety reserves,
– efficiency and effectiveness of airport processes in relation to the security of airport operations.

2. Airport as a system

The problem of assigning aircraft to sleeves (gates) can be seen as a task scheduling problem involving the assignment of activities, and in this case the flight to the service site, i.e. the sleeve. This operation can be carried out taking into account various combinations as well as different purposes. Scheduling is therefore a decision problem regarding the allocation of tasks to resources in a given time.

Narciso et al., (2015) create an algorithm for robust gate assignment from an airport management perspective with used formal modeling approach based on colored Petri nets. The results show that by reducing uncertainty in the arrivals and departures is possible to minimalize infrastructure investments without affecting QoS indicators. Several other solution techniques were reviewed to use generic algorithms. Benlic et al. (2017) worked for optimizing liner combination of nine gate allocation and they used for these two heuristic algorithms to tackle the problem. Given the nonlinearity of the considered problem formulation, they propose an approach that fallows general framework Breakout Local Search (BLS). Results show the usefulness of BLS for GAP, and accentuate the contribution of the multi-type perturbation adaptive perturbation mechanism to the performance of the proposed approach. Multi-objective gate assignment show Zhang et al. (2016). To reduced possibility of flight conflict and improve QoS, multi-objective gate assignment model has been created. The biogeography-based optimization algorithm is used to solve the proposed model with a new method for estimating the conflict probability. The results show that the robustness increase greatly and the probability of flight conflicts decreases, additionally those algorithms are effective to solve the proposed model and easy to find out optimal solutions. Behrends and Usher in 2017 used a genetic algorithm that is used to determinate the gate assignment scheme resulting in minimum delay minutes for a given schedule. This can decrees costs associated with moving freight or passengers for one point to another. Van Schaijk and Visser [15]in 2017 present a new method to improve the robustness of solutions to the Flight-to-Gate Assignment Problem (FGAP). Their goal is to decrees the need for gate

re-planning due to unpredicted flight schedule disturbances. The model proposed here features a computational complexity that is not significantly different from the basic multiple time slot FGAP formulation from which it originates. The results of this concept give great promise for further development.
The subject of the research presented in this article is to support decisions made during traffic management on the ramp and within the airport, i.e. the operation of assigning aircraft to gates. Based on the assumption that the airport is a kind of system whose purpose is to operate aircraft, it is necessary to define the concept of the system. There are many definitions in the literature on the subject. They occur in many scientific areas and are constructed due to various applications. The accuracy of the proposed definitions is proportional to the volume of the class of systems concerned. Detailed analyzes of the concept of "system" in application to transport and movement can be found in numerous works (Adacher et al., 2018; Leszczyński, 1994; Sienkiewicz, 1983 and 1994). The authors of these works indicate that the concept of the system, regardless of the area of application, is defined taking into account its basic properties, concerning:

- the need to separate it from the environment (open, closed or partially isolated systems),
- the need to build it from elements (subsystems) interacting in a certain way,
- the function performed by the system (there are no pointless systems or those whose internal functioning mechanisms are not subject to logical laws),
- the need for limited variability in time defined on the basis of the purpose of the (technical) system).

The system and its functions result from the type of elements and the relationship between them and between the system and its surroundings. The nature of the connections between the elements of the system defines its structure (Adacher et al., 2018; Jacyna, 2008; Sienkiewicz 1983, 1987 and 1994).
The purpose of the airport's operation as a system is to organize the movement of aircraft on the tarmac and immediately before and after take-off. It is focused on:

- maintaining an adequate level of passenger and passenger safety as well as property in the area of potential threat resulting from the nature of air traffic,
- reducing the arduousness of air operations for the environment, including the natural environment,
- increasing airport capacity.

This goal requires the airport to have adequate equipment to service the movement of aircraft in accordance with the rules of on-board traffic and the flight schedule.
The tasks of the airport system result from planned (and unplanned) take-off and landing operations, ground handling of airplanes as well as passenger and baggage handling, which in turn are correlated with the demand for air transport in a specific region, the offer of carriers, the airport's service capacity and technical capabilities of implementation and air traffic security.
Given the above, for the uniqueness of further considerations the **airport as an aircraft service system** has been defined as follows::
A set of technical, communication and organizational measures as well as ground infrastructure elements, having the ability to buffer and move aircraft operating on an apron or in the air immediately before and after landing and take-off operations, which aims to ensure the safety and adequate efficiency of processes.
Due to the variety of functional structures of airports, legal regulations, communication systems, generation of technical solutions and their sensitivity to interference - the task of airport modeling and assessment is complex and important. Schematic functioning of the airport in an environment where there are disturbances and threats is shown in Fig. 1.
From a systemic point of view, the airport can be treated as a system using synergistic interaction of elements, hence it can be formally written as an ordered three:

$$\boldsymbol{MSL} = \boldsymbol{S}(\boldsymbol{A_{SL}}, \boldsymbol{E_{SL}}, \boldsymbol{R_{SL}}) \tag{1}$$

where:
$\boldsymbol{MSL}$ – system point of view of the airport,
$\boldsymbol{A_{SL}}$ – set of airport system elements, e.g.., $\boldsymbol{A_{SLCL}} = \{A_1, A_2, \dots A_m\}$,
$\boldsymbol{E_{SL}}$ – set of attributes (properties) of system elements - airports, $\boldsymbol{E_{SL}} = \{E_1, E_2, \dots, E_n\}$,
$\boldsymbol{R_{SL}}$ – set of relations between elements and attributes of the system - airports $\boldsymbol{R_{SLCL}} = \{R_1, R_2, \dots, R_z\}$.

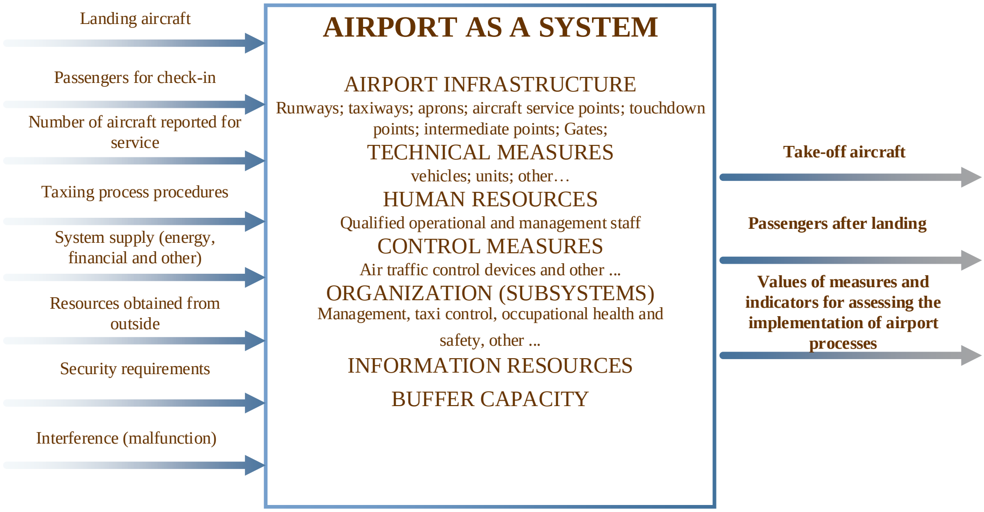

Fig. 1. The airport as a system and its surroundings

In physical terms, an **airport** is a separate area on land, water or other surface, in whole or in part, intended for take-offs, landings and ground movement of aircraft, together with permanent objects and construction equipment located within its borders, entered in the airport register. On the other hand, the set of devices and facilities used to operate the aircraft in the area of the ground movement field is defined as (Izdebski, 2018). The above issues are related to those occurring e.g. in warehouse facilities or production plants (e.g. Kłodawski et al., 2018 or Jacyna et al., 2018), differ only in the basic assumptions.

The problem of ground movement at the airport is the planning of aircraft movements between airport facilities so as to eliminate traffic conflicts in the most technically, economically, ecologically and environmentally efficient manner (Zieja and Gołda, 2014; Kwasiborska and Malarski, 2009).

Each arriving aircraft is directed from the runway to a stopping place on the apron, at the gate or service area. The departing aircraft must be directed from your current parking position to the runway. Ground movements are carried out in the taxiway network connecting airport elements. Because taxiways connect runways and stations, they become a key resource in the taxi process. Taxiways for departing planes traveling from fixed gates and stopping places to runways are predetermined and if there is a conflict with another aircraft, one of them must stop and wait. This results in delayed departures and potential delays in reaching the destination or increased cost of travel due to the need to increase speed (Adacher et al., 2018).

An important aspect of proper air traffic management at an airport is the maintenance of adequate performance, which has a direct impact on the safety and reliability of flights (Gołda and Zieja, 2014 and 2014b; Zieja et al., 2017).

3. Characteristics of service stations

Generally, service posts differ in the number of aircraft served. Therefore, the set of service station numbers (gates) not adapted to service large aircraft ***PGB*** will take the following form and at the same time will be a subset of the set of ***GB*** gate numbers:

$$\boldsymbol{PGB} \subseteq \boldsymbol{GB} = \{1, \dots, k, l, \dots, PGB\}$$

with the values k, l representing gate numbers.

It is therefore necessary to formulate a set of numbers for large aircraft/flights **PI**. This set will be a subset of the set of flight/ airplane numbers:

$$\boldsymbol{PI} \subseteq \boldsymbol{I} = \{1, \dots, i, j, \dots, PI\} -,$$

where i, j are aircraft/flight numbers.

The allocation of flights / aircraft to service stations is part of the airport operations plan. According to this plan, at the gates, each aircraft is served at certain time intervals, which are later called time windows. Hence, on the set of flight/aircraft numbers $\boldsymbol{I}$ the following mappings were set to convert its elements into a set of moments $\boldsymbol{T}$ of the form:

$a: \boldsymbol{I} \longrightarrow \boldsymbol{R}^{+}$
$b: \boldsymbol{I} \longrightarrow \boldsymbol{R}^{+}$
where size a_i has an interpretation of the beginning of the time window for operating the i-flight/aircraft.

At the same time, the service time of the i-th flight/aircraft at the gate was designated as dt_i. Flight / aircraft service outside the designated time window (untimely service) is associated with a penalty specified in this work by kk_i, whereby kk_i as an interpretation of the unit cost of penalty for untimely service at the gate of the i-th flight/plane.
In the model being developed, the convenience of passengers transferring at the airport was used as the basic criterion for the allocation of flights/aircraft to service stations. In this regard, the minimization model reflects the time that passengers have when transferring between two selected flights/ aircrafts. his time is denoted by w_{kl}, where its value has the interpretation of the transition time between k-th and l-th aircraft service gate. In turn, the number of passengers transferring between the i-th and j-th flight/aircraft was marked by np_{ij}.
The variables describing the planning of the allocation of aircraft to gates relate to:
- allocation of a given flight / aircraft to a given gate,
- start time of service at a given gate,
- order of takeoff and landing of aircraft, which affects their assignment to the gates.

Binary variables are::
- $x_{ik} \in \{0,1\}$ – decision variable taking the value 1 if the i-th flight has been allocated to the k-th gate; otherwise it is 0;
- $h_{ij} \in \{0,1\}$ – a decision variable with a value of 1 if the i-th plane leaves no later than the landing of the jth plane; otherwise it is 0.;
- $z_{ij}^{kl} \in \{0,1\}$ – decision variable taking the value 1 if the i-th aircraft has been assigned to the k-th gate and the i-th aircraft to the l-th gate; otherwise it is 0.

In turn, real variables are:
- c_i – variable interpreting the moment at which the aircraft begins to use the gate to which it has been assigned.

The complexity of airport management has increased significantly. Delays or accidents can happen if operations are not performed properly and the domino effect can affect all airport operations. At airports, tasks related to the problem of AGAP (*airport gate assignment problem*) gate allocation are one of the most important daily operations. The goal of the task is to assign each flight (aircraft) to the available gate while maximizing both passenger convenience and airport operational efficiency. Large airlines usually need to manage different airport gates in the most efficient way in a dynamic operational environment. This requires solutions that provide the ability to change and update gate assignment data in real time. Such a system should also ensure robustness and effectiveness of interference management, while maintaining security, while minimizing costs.
The goals of analyzing the problem of gate allocation can be varied and depend on the point of view. From the airport owner's point of view, the goal is:
- maximizing the time of using the available gates (gates) of the terminal,
- minimization of conflict situations during the allocation of goals,
- minimizing the number of unassigned aircraft,
- minimizing aircraft delays due to waiting for gate assignment.

From an airline point of view, the goal of gate allocation optimization is:
- maximizing passenger satisfaction by minimizing the distance between gates (for transfer passengers),
- minimizing the distance from the runway to the gate.

The vast majority of models regarding the allocation of gates for aircraft are focused on minimizing the distance of passage of passengers changing between the distinguished gates. It is important in this situation to start operating the aircraft at the gate as soon as possible. Therefore, the rest of the work presents a mathematical model for minimizing the transit time of transferring passengers between gates, including penalties for delays in operating a given aircraft. In addition, the model assumes that not all gates can support all types of aircraft. In this regard, the focus was on the characteristics of the aircraft regarding its size.

3.1. Data identification for the model

The data necessary to develop a mathematical model for the allocation of flights to gates due to the minimization of the transit time of passengers transferring between planes, taking into account the penalties for delaying the start of aircraft service, is presented below.

$\boldsymbol{I}=\{1,\ldots, i, j, \ldots, I\}$ – set of flight numbers,

$\boldsymbol{PI} \subseteq \boldsymbol{I} = \{1,\ldots, i, j, \ldots, PI\}$ – set of flight numbers with large aircraft,

$\boldsymbol{GB}=\{1,\ldots, k, l, \ldots, GB\}$ – set of gate numbers for aircraft/flights,

$\boldsymbol{PGB} \subseteq \boldsymbol{GB} = \{1,\ldots, k, l, \ldots, PGB\}$ – set of gate numbers not adapted to service large aircraft,

a_i – start of the service time window at the gate of the i-th flight,

b_i – end of service window at the gate of the i-th flight,

dt_i – gate occupation time for the i-th flight,

kk_i – unit cost of penalty for untimely service of the i-th flight,

w_{kl} – passenger transit time between gates k and l,

np_{ij} – number of passengers moved between flight i and and flight j,

M – maximum time that can be used in conflict situations,

OD_{ij} – maximum allowable distance between gates for passengers on flights i and j.

Defining decision variables

$$\boldsymbol{X} = [x_{ik}] \quad x_{ik} \in \{0,1\}, \quad i \in \boldsymbol{I} \quad k \in \boldsymbol{K}$$

$$\boldsymbol{C} = [c_i] \quad c_i \in \boldsymbol{N}, \quad i \in \boldsymbol{I}$$

$$\boldsymbol{H} = [h_{ij}] \quad h_{ij} \in \{0,1\}, \quad i, j \in \boldsymbol{I}$$

$$\boldsymbol{ZB} = [z_{ij}^{kl}] \quad z_{ij}^{kl} \in \{0,1\}, \quad i, j \in \boldsymbol{I} \quad k,l \in \boldsymbol{GB}$$

where:

– $x_{ik} = 1$, if the i-th flight has been allocated to the k-th gate; otherwise it is 0;

– c_i – the time when the aircraft begins to use the gate to which it has been assigned;

– $h_{ij} = 1$, if the i-th plane leaves no later than the landing of the jth plane. 0 otherwise;

– $z_{ij}^{kl} = 1$ if the i-th aircraft is assigned to the k-th gate and the i-th aircraft is assigned to the l-th gate; otherwise it is 0.

Defining the criterion function

The criterion function has an interpretation of minimizing the travel time of passengers transferring between two aircraft assigned to two different gates:

$$\sum_{i=1} kk_i (c_i - a_i) + \sum_{i=1} \sum_{j=1} \sum_{k=1} \sum_{l=1} np_{ij} w_{kl} z_{ij}^{kl} \to \min \tag{2}$$

Defining the layout of constraints

Restrictions imposed on the values of decision variables:

– Each aircraft can only be assigned to one gate,

$$\forall i \in I \qquad \sum_{k=1} x_{ik} = 1 \tag{3}$$

– The gate cannot operate two aircraft at the same time,

$$\forall i, j \in I \wedge i \neq j \qquad \forall k \in GB \qquad h_{ij} + h_{ji} \geq z_{ij}^{kl} \tag{4}$$

– Assuming that a large number of transfers take place between two planes (a significant proportion of passengers on the i-th flight change to the j-th flight), these flights should be assigned to service at gates located close to each other:

$$\forall i, j \in I \wedge i \neq j \qquad \sum_{k=1} \sum_{l=1} x_{ik} w_{kl} x_{jl} \leq OD_{ij} \tag{5}$$

– Large aircraft cannot be operated on gates not adapted to their operation:

$$\forall i \in PI \quad \forall k \in PGB \qquad x_{ik} = 0 \tag{6}$$

– Restrictions on the value of decision variables regarding the allocation of aircraft to gates:

$$\forall i, j \in I \qquad \forall k \in GB \qquad z_{ij}^{kl} \leq x_{ik} \tag{7}$$

$$\forall i, j \in I \qquad \forall k, \mathrm{l} \in GB \qquad z_{ij}^{kl} \leq x_{jl} \tag{8}$$

$$\forall i, j \in I \qquad \forall k, \mathrm{l} \in GB \qquad x_{ik} + x_{jl} - 1 \leq z_{ij}^{kl} \tag{9}$$

– Restrictions indicating that each flight should begin and end service at the gate in the designated time window:

$$\forall i \in I \qquad c_i \geq a_i \tag{10}$$

$$\forall i \in I \qquad c_i \leq b_i - dt_i \tag{11}$$

- Restrictions on the value of decision variables regarding the order of arrival/departure of aircraft:

$$\forall i, j \in I \quad (c_i + dt_i) - c_j + h_{ij}M > 0 \tag{12}$$

wherein $h_{ij} = 1,\ \text{gdy}\,(c_i + dt_i) \le c_j$. This means that $h_{ij} = 1$, when the *i*-th aircraft/flight departs before or at the moment when the gate opens to accept the *j*-th aircraft.

$$\forall i, j \in I \quad (c_i + dt_i) - c_j - (1 - h_{ij})M \le 0 \tag{13}$$

wherein $h_{ij} = 0,\ \text{gdy}\,(c_i + dt_i) > c_j$. This means that $h_{ij} = 0$, when the *i*-th aircraft/flight departs after the moment when the gate opens to accept the *j*-th aircraft.

4. Conclusions

The positioning of aircraft on the apron must be based on thoughtful decisions, taking into account many aspects of scheduling and finding the optimal stopping place while maintaining the safety of passengers and aircraft. The approach and methodology described in the article was used to create a simulation tool that allows:

- depicting the full surroundings of the airport, including: the configuration of runways and taxiways, aprons, airports (navigational aids, obstacles, etc.), natural relief of the area surrounding the airport, man-built facilities (hangars, pilot's cottage, etc.) and obstacles seen from the tower;
- mapping of vehicles used at airports (tugs, tankers, buses, cleaners, fire brigade, ambulance, FOLLOW ME vehicles, snow plows, etc.);
- mapping of atmospheric conditions around the airport apron, including: changing cloud layers, different levels of horizontal and vertical visibility, changing weather conditions, pressure drops and increase, cloud cover, visibility, wind direction and speed, etc ;
- making changes in the flight parameters of aircraft, primarily their speed and behavior in different phases (e.g. collision with another aircraft, collision with a bird, etc.);
- analysis of scenarios of decision-making situations taking into account various disturbances (failures) that require the appropriate reaction of the decision maker.

It should be remembered that the dynamics and development of aviation imposes an obligation to constantly improve and develop emerging models in order to improve aviation safety.

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