# OPTIMIZATION OF PASSENGER FLOW ON THE AIRPORT APRON

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***Resume***

In this article is addressed the optimization problem of assigning aircraft to parking stands on the apron of international regional airports. The goal was to position an aircraft on the airport apron in a way that complies with operational, capacity, and safety constraints while optimizing the value of the selected optimization criterion. In contrast to other commonly published approaches, problem considered here focuses on minimizing passenger transport between the parking stands and the terminal via airport buses. To solve this problem, a linear integer programming model is formulated and solved using the Xpress-IVE optimization software. The model's functionality is tested using real operational data from Ostrava International Regional Airport.

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## 1 Introduction - motivation for the solution

The growing density of air traffic, pressure from airlines to reduce turnaround times, and increasingly stringent operational and safety requirements place high demands on all airports in terms of check-in process organization. In an environment where time buffers are gradually shrinking and where even a minor delay can trigger a chain reaction of further irregularities, the efficient allocation of limited airport resources, parking stands, gates, personnel, and support equipment becomes increasingly important. One of the key planning tasks at airports is assigning a parking stand (or gate) to an aircraft on the airport apron. The choice of a stand on the airport apron not only affects the smooth handling of the aircraft and the flow of the handling process, but also contributes to maintaining acceptable passenger comfort and minimizing the risk of operational conflicts.

The issue of assigning an aircraft at stands on the airport apron has long been studied in the technical literature as part of an optimization problem known as the Gate Assignment Problem (GAP), also referred to as the Flight Gate Assignment Problem (FGAP) or the Stand Assignment Problem (SAP). The problem of assigning departing aircraft at stands on the airport apron is applicable to both hub airports and regional or point-to-point airports, although the structure of the optimization objectives differs somewhat in both types of environments. At non-hub airports, optimization is often focused on minimizing the total distance or time passengers spend traveling between the aircraft and the terminal, or while moving within the terminal, and on ensuring smooth check-in with a relatively limited number of resources.

The development of this field and the methods for solving this problem can be traced back to the 1980s, with the original impetus being an effort to support the decision-making of airport operations managers and to increase the efficiency of utilizing the limited capacity of the airport apron while handling multiple aircraft simultaneously. Gradually, however, it became clear that operational feasibility in terms of passenger comfort during their journeys is not the only requirement: criteria such as reliability and robustness against uncertainties (e.g., during variable apron occupancy times or when flight arrivals are delayed) are also coming to the fore, as well as the minimization of conflicts, carrier preferences, and the creation of links to terminal processes.

The most significant optimization criterion from the passengers' perspective is the total distance travelled, or its time equivalent, between the terminal and the gates on the airport apron. In practice, passenger movement can be achieved in several ways: via boarding bridges, on foot across the airport apron, or by airport shuttle buses. The chosen passenger transfer method significantly influences both passenger comfort and operational times and organization on the airport apron.

At airports where the boarding bridges have not been constructed (which is the case at Ostrava International Regional Airport) and the gates are not too far from the terminal, passenger movement on foot across the airport apron is preferred.

Passenger bus transport is generally organized for situations where there is a shortage of parking stands within the walking distance, for seasonal peaks, for operations with highly variable flight schedules, or for airports with infrastructure limitations (a limited number of parking stands on the airport apron directly connected to the terminal). Last but not the least, it is also necessary to consider the risks associated with the concurrence of multiple passenger transfers, for example, unwanted contact between passenger flows from different aircraft, crowding of passengers, and the emergence of potentially conflictual situations on the airport apron.

However, the necessity of using the bus transport for passengers across the airport apron fundamentally alters the nature of the problem: additional capacity and time-related variables enter the problem of optimal aircraft allocation to apron stands (e.g., bus availability, travel times, type of passenger transfer, time coordination with ground handling, or constraints resulting from passenger flow movements on the apron). Optimization must then aim for an allocation that minimizes the overall impact of transportation on aircraft turnaround, delays, and resource utilization, while also respecting technical, capacity, and safety constraints of operations.

In this article the focus was on optimizing the allocation of aircraft on the airport apron, with explicit consideration of bus transportation on the apron. The aim of the article was to present a mathematical model for assigning aircraft at stands on the airport apron, which, in addition to standard operational constraints, also incorporates constraints arising from passenger bus transport requirements, thereby contributing to improved coordination of handling processes (to facilitate the transport of passengers across the airport apron by bus in cases where there are overlapping passenger flows on the airport apron). The proposed approach is designed as a practical decision-making tool that can support both planning and operational management, particularly in situations with a higher concentration of aircraft on the apron and limited availability of parking stands within walking distance.

## 2 Literature review

A large number of papers addressing the issue of aircraft parking allocation on airport aprons have been published in the literature.

In article Bihr, 1990 [1] was addressed the problem for airports where passengers transfer to connecting flights. To solve this problem, the author used exact algorithms based on mathematical programming. The goal was to minimize the total transfer distance that passengers must travel from the exit of the aircraft on which they arrived to the gate for their next connecting flight. The main constraints included in the model are the requirement to assign exactly one parking stand to each aircraft being handled and the requirement that each parking stand be used by exactly one aircraft.

The approach published in Yan et al., 2002 [2] addressed the problem at Taipei Airport in Taiwan. To solve the problem, the author proposed a stochastic model and uses a heuristic greedy algorithm. The optimization criterion is again the total distance passengers must travel from the gate to the aircraft, and the goal of optimization is to minimize this value. The main constraints incorporated into the model include standard constraints - each flight must be assigned to only one gate, and two aircraft (in the case of time-conflicting flights) cannot be assigned to the same gate. The model incorporates randomness in the form of flight delay values and the time intervals between the check-ins of individual aircraft at a given gate.

The main motivation for the work Lim et al., 2005 [3] was the need to respond to operational changes in the daily schedule for assigning arrival and departure gates to specific flights. To solve the problem, the author used the heuristic approaches (the "Greedy algorithm" and a metaheuristic approach based on the "Tabu-search" strategy). The decision-making process also takes into account the so-called penalties, which are applied when an aircraft is waiting for the stand to be vacated by the previously checked-in aircraft. The goal of the optimization was to minimize both the total transfer distance for passengers transferring between connecting flights and the total penalty value associated with the time aircraft spend waiting for check-in at occupied gates.

The study Tang et al., 2010 [4] was focused on the operational allocation (rescheduling) of stands on the airport apron to delayed flights. The authors used mathematical programming methods to solve the problem. In the event of delays to flights currently being handled, gates are dynamically assigned to all other flights in the given planning period so as to minimize the total delay time of all aircraft in that planning period compared to the original cumulative time when no delays were anticipated. The model accounts for three types of constraints: each flight must be assigned to only one gate; two aircraft cannot be assigned to the same gate if they conflict in time; and aircraft cannot be assigned to two adjacent stands (e.g., due to impossible manoeuvrability resulting from wingspan). Computational experiments were conducted under the conditions of Taipei International Airport in Taiwan.

In article Dijk et al., 2019 [5] an approach was presented for developing a tactical aircraft deployment plan on airport aprons and was carried out in collaboration with Guarulhos International Airport in São Paulo. To evaluate the effectiveness of the tactical deployment plan, in the study were examined and tested three mathematical programming models that differ in their optimization criteria. The optimization criteria in the models include the total distance that transfer passengers must travel (when transferring to connecting flights), the number of aircraft tows (due to unproductive gate utilization), and the revenue generated by airport retailers (creation of pedestrian corridors in the terminal around sectors with a high density of retail stores). A unique aspect of this work is the incorporation of the airport's commercial revenue indicator into the optimization problem and the evaluation of its effectiveness in relation to the other objectives described above.

Article Silva, 2019 [6] is a case study developed for Lisbon Airport based on historical data. The author proposed a heuristic approach to minimize operating costs and maximize the efficiency of the check-in process. The algorithm for optimizing the gate allocation was based on arrival and departure times, aircraft size, expected passenger flows, and the availability of individual gates. Experiments have shown that the proposed algorithm is capable of reducing the number of necessary operational gate changes and increases the utilization of available gates compared to the current manual approach used at the airport.

Miculka et al., 2025 [7] have dealt with Gate Assignment Problem at Krakow Airport. Binary linear programming model is proposed that assigns flights to apron stands and arrival/departure gates so as to minimize the total passenger walking distance while respecting operational constraints such as stand conflicts, gate compatibility, time-overlapping flights, and collision stands. In the study were emphasized passenger-oriented objectives and the model to a real airport data was applied. The authors conclude that the model is a useful decision-support tool for medium-term airport planning,

However, none of the above-mentioned studies mentions the possibility of passengers moving on foot across the airport apron in combination with their transport by airport buses on the apron. This issue of the optimization problem involving the integration of passenger bus transport within the apron is mentioned only marginally; among the available studies, only Diepen et al., 2008a [8], Diepen et al., 2008b [9], Diepen et al., 2013 [10], Li et al., 2024 [11] are worth noting, as they include references to the integration of passenger bus transport into the handling process.

In the three papers [8-10], authors addressed the problem of assigning aircraft to parking stands at Amsterdam-Schiphol Airport and the subsequent planning of passenger transport via airport buses. They solved both problems as a joint integer linear programming problem in combination with the column generation method. The objective of the optimization was to minimize the robust cost. The robust cost includes the costs of assigning flights to gates and ensuring the subsequent transport of passengers by airport buses, and is extended to include a penalty in the event that an aircraft is not assigned a gate or the subsequent transport of passengers by airport buses is not ensured. The model accounts for several types of constraints - each flight is either assigned to a single gate or its non-assignment is penalized; adherence to a predefined minimum preference level for individual gate types; consideration of the number of driver shifts; and the scheduling of airport bus trips, or penalties for failing to provide them. Authors in article [9] extended article [8], by including a heterogeneous fleet of airport buses. Unlike the model presented here, the model in articles [8-10] required the prior creation of a gate plan and a bus route plan; it did not include the possibility of combining pedestrian crossings and bus routes across the airport apron, and it did not address the existence of separate gates for Schengen and non-Schengen flights.

In article Li et al. [11] the classic problem of assigning departing aircraft at stands on the airport apron was extended to include the so-called multipurpose stands was extended which can serve either a single wide-body aircraft or two narrow-body aircraft simultaneously, and simultaneously considers the assignment of departing aircraft to both terminal and remote stands. The authors formulated a multi-criteria model with four objectives: to maximize the number of passengers handled at apron stands near the terminal, to minimize the total walking distance for passengers, to minimize, $CO_2$ emissions associated with the use of remote apron stands, and to minimize the total distance travelled by airport buses. In study again was not included the possibility of combining pedestrian crossings with bus crossings across the airport apron.

## 3 Design of a mathematical model

### 3.1 Statement of the problem

The set of aircraft being processed is given $I(|I| = n)$, set of parking stands on the apron $S(|S| = p)$. Aircraft Time Collision Matrix $A$ (when a time conflict arises between aircrafts $i \in I$ and $k \in I$, then $a_{ik} = 1$, otherwise $a_{ik} = 0$) and the set of passenger movements on the apron $K$. Set $K$ will have two elements $(K = \{1,2\})$, where the value 1 always represents passenger movement from the parking area to the arrival gate, and the value 2 always represents passenger movement from the departure gate to the parking area. A matrix of time conflicts in passenger movements is also available $C$, if there is a time conflict involving the movement of passengers of type $k \in K$ for an aircraft parked at stand $s \in S$, and a time conflict involving the movement of passengers of type $l \in K$ for an aircraft parked at stand $p \in S \backslash \{s\}$ then $c_{kslp} = 1$; otherwise, $c_{kslp} = 0$). An estimated time of 15 minutes is allowed for passengers to walk across the apron, and 10 minutes for travel by airport bus. If buses are used to transport passengers from aircraft $i \in I$ across the airport apron, then the number of buses required to transport passengers to aircraft $i \in I$ upon arrival $l = 1$ or before departure ($l$ = 2), denoted as $b_{il}$, is defined (this number can be derived based on the number of passengers on a given day; when creating a forecast plan, we can consider both values to be the same and derive them from the aircraft's capacity).

Furthermore, the required times $t_{iks}$ are available (the time for the bus to arrive at aircraft $i \in I$ located at stand $s \in S$ ($k$ = 1) or at the departure gate for aircraft $i \in I$ at stand $s \in S$ ($k$ = 2)), the bus travel times between the terminal and the stands on the airport apron $T_{iks}$ (the bus travel time, including the time required for passengers to board and disembark from aircraft $i \in I$ at stand $s \in S$ to the arrival gate ($k$ = 1) or from the departure gate to aircraft ($k$ = 2)) and bus trips without passengers between individual stands on the apron $\tau_{sr}$, where $s \in S$ and $r \in S$.

Decisions are made regarding the assignment of individual aircraft at stands, the choice of method for transporting passengers between the aircraft and the terminal (by bus or on foot), and the connections between individual bus services, including bus arrivals from the garages and their departures to the garages. The optimization criterion is the total number of bus movements caused by the need to use airport buses while simultaneously avoiding time-conflicting movements of passenger flow on the apron, including the arrival of airport buses from the garages (parking area) and the return of airport buses to the garages (parking area).

The result of the optimization problem will therefore be an allocation of aircraft at stands and a method for organizing passenger movement, including minimizing bus movement, such that all operational, scheduling, and safety requirements of the model are met.

### 3.2 Mathematical model

To model elementary decisions in the mathematical model, seven groups of variables are introduced:

$u_{iks}$ a binary variable modelling the transfer of passengers by bus from aircraft $i \in I$ at stand $s \in S$ to the arrival gate ($k$ = 1) or from the departure gate to aircraft $i \in I$ at stand $s \in S$ ($k$ = 2), where, after the optimization calculation is complete $u_{iks}$ = 1, then from aircraft $i \in I$ at stand $s \in S$ to the arrival gate or from the departure gate to aircraft $i \in I$ at stand $s \in S$ passenger transport by bus will take place; if, after the optimization calculation is complete $u_{iks}$ = 0, then, from aircraft $i \in I$ at stand $s \in S$ at the arrival gate or from the departure gate to aircraft $i \in I$ at stand $s \in S$ passenger transport by bus will not take place;

$v_{iks}$ a binary variable modelling the movement of passengers on foot from aircraft $i \in I$ at stand $s \in S$ to arrival gate ($k$ = 1) or from departure gate to aircraft $i \in I$ at stand $s \in S$ ($k$ = 2), where, after the optimization calculation is complete $v_{iks}$ = 1, then from aircraft $i \in I$ at stand $s \in S$ ($k$ = 1) to the arrival gate or from the departure gate to aircraft $i \in I$ at stand $s \in S$ passenger walk-through occurs when, after the optimization calculation is complete $u_{iks}$ = 0, then from aircraft $i \in I$ at stand $s \in S$ to the arrival gate or from the departure gate to aircraft $i \in I$ at stand $s \in S$ passenger walk-through will not occur;

$w_{is}$ a binary variable modelling the assignment of aircraft $i \in I$ at stand $s \in S$, where, after the optimization calculation is complete $w_{is}$ = 1, then aircraft $i \in I$ is assigned at stand $s \in S$, if, after the optimization calculation is complete $w_{is}$ = 0, then aircraft $i \in I$ will not be assigned to parking stand $s \in S$;

$x_{iksjlr}$ the number of buses traveling after transporting passengers from aircraft $i \in I$ at stand $s \in S$ to the arrival gate ($k$ = 1) or after transporting passengers from the departure gate to aircraft $i \in I$ at stand $s \in S$ ($k$ = 2) to transport passengers from aircraft $j \in I$ at stand $r \in S$ to the arrival gate ($l$ = 1) or to transport passengers from the departure gate to aircraft $j \in I$ at stand $r \in S$ ($l$ = 2);

$\alpha_{iksjlr}$ transfer following the transport of passengers from aircraft $i \in I$ at stand $s \in S$ to the arrival gate ($k$ = 1) or following the transport of passengers from the departure gate to aircraft $i \in I$ at stand $s \in S$ ($k$ = 2) the transfer of passengers from aircraft $j \in I$ at stand $r \in S$ to the arrival gate ($l$ = 1) or the transfer of passengers from the departure gate to aircraft $j \in I$ on stand $r \in S$ ($l$ = 2) will take place $(\alpha_{iksjlr} = 1)$ or will not take place $(\alpha_{iksjlr} = 0)$;

$y_{jlr}$ the number of buses arriving from the garages to transport passengers from aircraft $j \in I$ at stand $r \in S$ ($l$ = 1) or to transport passengers from the departure gate to aircraft $j \in I$ on stand $r \in S$ ($l$ = 2);

$z_{iks}$ the number of buses departing for the garages after transporting passengers from aircraft $i \in I$ at stand $s \in S$ ($k$ = 1) or after transporting passengers from the departure gate to aircraft $j \in I$ at stand $r \in S$ ($k$ = 2).

Summary of other symbols used in the mathematical model:

Sets:

$I$ set of aircraft being handled;

$S$ set of parking stands on the apron;

Matrix:

$A$ matrix of aircraft time conflicts;

$C$ matrix of permissible combinations of passenger movements related to aircraft positioning;

Constants in the mathematical model:

$n$ the number of aircraft being handled, i.e., $|I| = n$;

$p$ the number of parking stands on the apron, i.e. $|S| = p$;

$a_{ik}$ an element of the time-collision matrix; if aircraft $i \in I$ and $k \in I$ meet on the apron, then $a_{ik} = 1$, otherwise $a_{ik} = 0$;

$b_{il}$ the number of buses needed to transport passengers from the aircraft after arrival $i \in I$ ($l = 1$) or before departure ($l = 2$), is derived from the number of passengers on a given day; when creating a forecast, we can treat both values as equal and derived from the aircraft's capacity (pessimistic estimate);

$c_{kslp}$ an element of the matrix of time conflicts involving passenger movements related to aircraft positioning, where a time conflict occurs between passenger movements of type $k \in \{1,2\}$ for an aircraft located at a stand $s \in S$ and passenger movements of type $l \in \{1,2\}$ or an aircraft located at a stand $p \in S \backslash \{s\}$, then $c_{kslp} = 1$, otherwise $c_{kslp} = 0$;

$t_{iks}$ the time the bus arrives at aircraft $i \in I$ located at stand $s \in S$ ($k = 1$) or at the departure gate for aircraft $i \in I$ at stand $s \in S$ ($k = 2$), i.e., the location where passengers board the bus;

$T_{iks}$ the bus travel time (including the time required for passengers to board and disembark) from the aircraft $i \in I$ at stand $s \in S$ to the arrival gate ($k = 1$) or from the departure gate to the aircraft ($k = 2$), i.e., from the point where passengers board the bus to the point where they disembark;

$\tau_{sr}$ the time required for buses to move from stand $s \in S$ at stand $r \in S$.

The mathematical model has the following form:

$$\min f(u,v,w,x,y,z,\alpha) = \sum_{j \in I} \sum_{l \in \{1,2\}} \sum_{r \in S} y_{jlr} + \\ + \sum_{i \in I} \sum_{k \in \{1,2\}} \sum_{s \in S} \sum_{j \in I} \sum_{l \in \{1,2\}} \sum_{r \in S} x_{iksjlr} + \\ + \sum_{j \in I} \sum_{l \in \{1,2\}} \sum_{r \in S} z_{jlr} \quad (1)$$

subject to the following groups of constraints:

$$\sum_{s \in S} w_{is} = 1 \quad \text{for } i \in I, \quad (2)$$

$$w_{is} + w_{ks} \leq 1 \quad \text{for } i \in I, k \in I, a_{ik} = 1, s \in S, \quad (3)$$

$$w_{i1} + w_{k2} \leq 1 \quad \text{for } i \in I, k \in I, a_{ik} = 1, \quad (4)$$

$$w_{ks-1} + w_{is} + w_{ks+1} \leq 1 \text{ for } i \in I, k \in I, a_{ik} = 1, \\ s \in S \backslash \{1,p\}, \quad (5)$$

$$w_{ip-1} + w_{kp} \leq 1 \text{ for } i \in I, k \in I, a_{ik} = 1, \quad (6)$$

$$v_{iks} + v_{jlp} \leq 1 \text{ for } i \in I, j \in I, a_{ij} = 1 \\ \text{and } k \in \{1,2\}, l \in \{1,2\}, s \in S, p \in S \backslash \{s\}, \\ \text{and } c_{kslp} = 1, k < l, \quad (7)$$

$$y_{jlr} + \sum_{i \in I} \sum_{k \in \{1,2\}} \sum_{r \in S} x_{iksjlr} \leq M \cdot u_{jlr} \text{ for } j \in I, \\ l \in \{1,2\}, r \in S, \quad (8)$$

$$u_{jlr} + v_{jlr} \leq 1 \text{ for } j \in I, l \in \{1,2\}, r \in S, \quad (9)$$

$$u_{jlr} \leq y_{jlr} + \sum_{i \in I} \sum_{k \in \{1,2\}} \sum_{s \in S} x_{iksjlr} \text{ for } j \in I, \\ l \in \{1,2\}, r \in S, \quad (10)$$

$$y_{jlr} + \sum_{i \in I} \sum_{k \in \{1,2\}} \sum_{s \in S} x_{iksjlr} + b_{jl} \cdot v_{jlr} = b_{jl} \cdot w_{jr} \\ \text{for } j \in I, l \in \{1,2\}, r \in S, \quad (11)$$

$$y_{jlr} + \sum_{i \in I} \sum_{k \in \{1,2\}} \sum_{s \in S} x_{iksjlr} = \sum_{i \in I} \sum_{k \in \{1,2\}} \sum_{s \in S} x_{jlriks} + z_{jlr} \\ \text{for } j \in I, l \in \{1,2\}, r \in S, \quad (12)$$

$$t_{iks} + T_{iks} + \tau_{sr} \leq t_{jlr} + M \cdot (1 - \alpha_{iksjlr}) \text{ for } i \in I, \\ k \in \{1,2\}, s \in S, j \in I, l \in \{1,2\}, r \in S, \quad (13)$$

$$x_{iksjlr} \leq M \cdot \alpha_{iksjlr} \text{ for } i \in I, k \in \{1,2\}, s \in S, \\ j \in I, l \in \{1,2\}, r \in S, \quad (14)$$

$$u_{jlr} \in \{0;1\} \text{ for } j \in I, l \in \{1,2\}, r \in S, \quad (15)$$

$$v_{iks} \in \{0;1\} \text{ for } i \in I, k \in \{1,2\}, s \in S, \quad (16)$$

$$w_{is} \in \{0;1\} \text{ for } i \in I, s \in S, \quad (17)$$

$$x_{iksjlr} \in Z_0^+ \text{ for } i \in I, k \in \{1,2\}, s \in S, \\ j \in I, l \in \{1,2\}, r \in S, \quad (18)$$

$$\alpha_{iksjlr} \in \{0;1\} \text{ for } i \in I, k \in \{1,2\}, s \in S, \\ j \in I, l \in \{1,2\}, r \in S, \quad (19)$$

$$y_{jlr} \in Z_0^+ \text{ for } j \in I, l \in \{1,2\}, r \in S, \quad (20)$$

$$z_{iks} \in Z_0^+ \text{ for } i \in I, k \in \{1,2\}, s \in S, \quad (21)$$

The objective function in Equation (1) represents the optimization criterion - the total number of non-productive bus crossings during a given planning period. The constraint group in Equation (2) ensures that each aircraft is assigned exactly one parking stand on the airport apron. The constraint group in Equation (3) ensures that aircraft with time conflicts are not assigned the same parking stand on the airport apron. The constraint group in Equations (4) - (6) ensure that aircraft with time conflicts are not assigned adjacent parking stands on the airport apron (this requirement applies to Ostrava International Regional Airport). The constraint group in Equation (7) ensures that if a time conflict occurs between any two passenger movements on the airport apron, then at most one of them will be carried out on foot. The constraint group in Equation (8) ensures the recording of airport bus usage when they are used to transport passengers to a specific aircraft located at a specific parking position on the airport apron. The constraint group in Equation (9) ensures that if airport buses are used to transport passengers, pedestrian movement of passengers will not be possible, and vice versa. The constraint group in Equation (10) ensures that if buses are not used for a specific passenger transfer to a specific aircraft located at a specific gate, the registration variable $u_{jlr}$ will be equal to 0. The constraint group in Equation (11) ensures that the prescribed number of buses is provided for arrivals ($l$ = 1) and departures ($l$ = 2) or for passenger movement on foot across the apron. The constraint group in Equation (12) ensures that the number of buses provided for passenger boarding corresponds to the number of buses parked after passenger disembarkation in Equation (12). The constraint group in Equation (13) ensures that if bus transfers between aircraft services cannot be completed in time, they will not be permitted. The constraint group in Equation (14) ensures that if bus transfers between aircraft services are not permitted, they will not take place. The constraint groups in Equations (15) - (21) define the domains of the variables used in the model.

### 3.3 Case study of Ostrava airport

A computational experiment using the proposed model was conducted using data corresponding to a randomly selected day from the summer flight schedule at Ostrava Airport; the selected day falls within a period of increased demand typical of charter operations. This choice is particularly appropriate since during the summer peak season, there are more frequent overlaps of aircrafts being handled, and at the same time, the likelihood of situations where the bus transfers must be used and their coordination managed increases.

The basic input for the calculation is a flight schedule comprising 11 flights (or aircraft operations) for which arrival and departure times and origin/destination airports are known (Table 1). Time data are particularly important for determining apron occupancy intervals (the presence of an aircraft on the apron) and for scheduling passenger arrival and departure transfers.

A distinctive feature of the selected day is the presence of flights that extend past midnight: Flights 1 and 2 arrive the previous day (marked "(-1)" in Table 1) and remain on the airport apron until their morning departure times; Flight 11 also remains on the apron past midnight and departs the following day (marked "(+1)" in Table 1). From the model's perspective, this feature is significant because it requires consistent handling of time on a time axis longer than 0-24 hours (e.g., transformation to a continuous time axis) in order to correctly capture overlaps in apron occupancy and the continuity of bus loops.

A matrix of time conflicts between pairs of aircraft is then created from the flight schedule shown in Table 1; see Table 2. The matrix indicates whether the two aircrafts meet on the apron at the same time, thereby triggering conditions that prohibit assigning conflicting aircraft to the same parking stand. A value of 1 means that the given pair of flights is in a time conflict on the apron at that moment - they must not be assigned the same parking stand; a value of 0 means the opposite. The matrix of aircraft time conflicts in the computational experiment forms the basis for restricting the assignment of the same parking stands to multiple aircraft.

Departing passengers from flights 1 and 2, arriving passengers from flights 5 and 6, departing passengers from flights 4 and 6, arriving passengers from flight 5 and departing passengers from flight 4, arriving

***Table 1*** *Flight schedule for a randomly selected day during the flight season, [12]*

| Flight number | Arrival time | Arrival destination | Departure time | Departure destination |
|---|---|---|---|---|
| 1 | 18:20 (-1) | Heraklion | 04:40 | Tirana |
| 2 | 21:20 (-1) | Korfu | 04:45 | Rhodes |
| 3 | 00:10 | Warsaw | 05:30 | Warsaw |
| 4 | 09:10 | Hurghada | 10:00 | Hurghada |
| 5 | 09:30 | Tirana | 10:30 | Kavala |
| 6 | 09:35 | Malaga | 10:00 | Malaga |
| 7 | 14:00 | Djerba | 15:00 | Djerba |
| 8 | 14:50 | Enfidha | 15:50 | Enfidha |
| 9 | 15:20 | Kavala | 19:10 | Korfu |
| 10 | 18:35 | Hurghada | 19:35 | Hurghada |
| 11 | 23:55 | Korfu | 5:05 (+1) | Varna |

***Table 2*** *Aircraft collision matrix on the airport apron*

| Flight/Flight | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

***Table 3*** *Results of the computational experiment*

| Flight | Assigned stand on the apron | Arrival transfer | Departure transfer |
|---|---|---|---|
| 1 | 1 | on foot | on foot |
| 2 | 3 | on foot | on foot |
| 3 | 6 | on foot | on foot |
| 4 | 6 | on foot | on foot |
| 5 | 3 | on foot | on foot |
| 6 | 1 | on foot | by buses |
| 7 | 6 | on foot | on foot |
| 8 | 3 | on foot | on foot |
| 9 | 1 | on foot | on foot |
| 10 | 3 | on foot | on foot |
| 11 | 1 | on foot | on foot |

passengers from flight 5 and departing passengers from flight 6, arriving passengers from flight 6 and departing passengers from flight 4, arriving passengers from flight 8 and departing passengers from flight 7, arriving passengers from flight 9 and departing passengers from flight 8. For any bus transport of passengers across the Ostrava Airport apron, 2 buses are required for all aircrafts.

### 3.4 Computational experiment

The optimization calculation was performed using the Xpress - IVE optimization software on a PC with the following specifications: Intel(R) Core(TM) i9-10900X CPU @ 3.70GHz (3.70 GHz), 64.0 GB RAM.

The number of non-productive bus trips across the apron is 4. These are the non-productive trips from the starting point to Gate SD and from Parking Bay C1 back to the starting point (two buses are involved in both non-productive trips). A solution characterized by a lower number of unproductive bus trips is not permissible, because there is a time conflict between the flow of passengers moving toward the departure of Flight 6 (their movement on the apron occurs between 9:50 and 10:00) and passengers moving to the departure of flight 4 (located on the apron between 9:45 and 10:00). The results obtained are clearly summarized in Table 3.

The calculation took 0.7 seconds.

The resolution of the operational situation during the time period from 09:10 to 10:30, when multiple aircraft are experiencing timing conflicts on the apron, is shown in Figure 1.

Figure 1 shows the individual gates of the terminal (SD - Schengen departure, NSD - non-Schengen departure, NSA - non-Schengen arrival, SA - Schengen arrival) and the individual stands on the apron, designated C1 through C6. In the depicted operational scenario, aircraft 4 (at stand C6), 5 (at stand C3), and 6 (at stand C1) were present simultaneously on the apron. The time values for each stand represent the time intervals during which the aircraft apron handling takes place. Directed edges connecting the gate to the stands represent the movement of passenger flows on the apron; the values on these edges represent the time intervals during which passengers in these flows are present on the apron. Edges represented by a solid line represent passenger transfers via a pair of airport buses; other

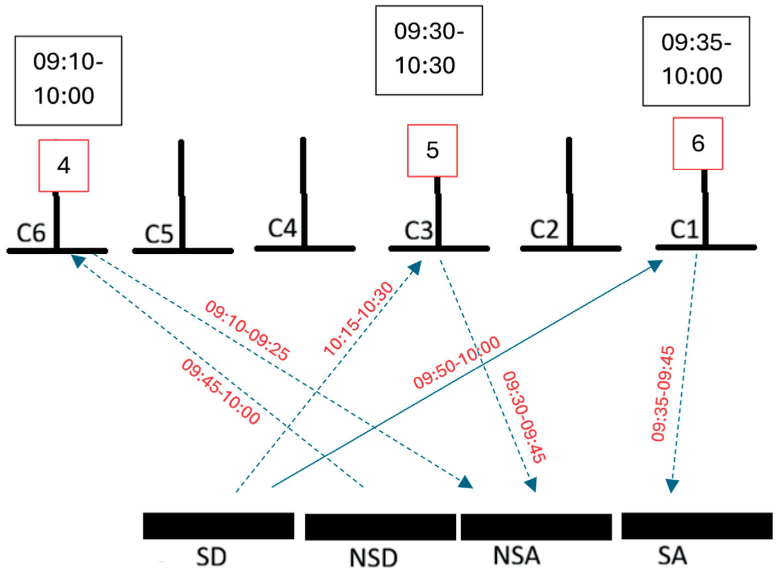


***Figure 1*** *Analysis of the operational situation during the time period 09:10-10:30 based on the results of models in Equations (1) - (21)*

edges represent passenger movements that take place on foot. Since a collision occurs at the edge connecting Gate NSD at Stand C6 and the edge connecting Gate SD at Stand C1, one of these transfers must be carried out using a pair of airport buses.

The dashed line in the image indicates a pedestrian crossing across the apron; the solid line indicates a bus crossing across the apron. The optimal solution has been achieved.

The optimization algorithm found an optimal solution with an objective function value of 4, meaning that a total of four bus trips were required to handle all the flights under consideration. At the same time, the algorithm determined the stands at which the individual aircraft would be parked and whether passengers would be transported between the aircraft and the terminal on foot or by bus.

The result shows that in the proposed solution, the aircraft used only stands 1, 3, and 6. Specifically, aircraft 1, 6, 9, and 11 were assigned at stand 1, aircraft 2, 5, 8, and 10 at stand 3, and aircraft 3, 4, and 7 at stand 6. The model was thus able to schedule operations so that even in the event of time conflicts, capacity and safety constraints were not violated.

From the perspective of passenger transfer methods, the result is very favourable. Of the total 22 operations (11 arrivals and 11 departures), 21 were carried out via pedestrian transfer, and bus transport was necessary in only one case, namely for the departure operation of aircraft 6 at stand 1.

The output further shows that two buses were used for this bus transport; they were brought from the garages to the departure service for aircraft 6 and returned to the garages after the transport was completed. The model thus not only determined the allocation of aircraft at stands but also planned bus transportation to achieve the most efficient operational plan in terms of bus utilization.

## 4 Discussion

In this article was addressed the issue of optimal aircraft positioning on an airport apron, with the option of using buses to transport passengers across the apron. In the article is presented a proposal for a new mathematical model that allows for testing the effectiveness of airport bus routing in the event of conflicting passenger flows on the apron. The optimization criterion is the total number of unproductive trips made by a pair of airport buses across the apron, and the goal of optimization is to minimize the total number of unproductive trips. The optimization criterion could also, for example, minimize the total length (or duration) of the trips. This would likely result in a further increase in the efficiency of bus operations. However, since at Ostrava Airport the distance from the terminal to the farthest parking stand is approximately 200 m (distances are not a critical factor), it is also possible to work with the number of trips.

In terms of results, it is therefore expected that the placement of aircraft on the apron will be designed to use the smallest possible number of buses and to minimize the number of unproductive bus trips. The proposed model includes constraints representing the requirements for the temporal coordination of pedestrian and bus movements of passengers across the airport apron, while simultaneously establishing safety constraints that eliminate collisions between passenger flows on the apron. This reflects the real-world operational conditions at Ostrava Regional Airport, where bus transfers are utilized as needed. Calculations performed using the proposed model confirmed these expectations.

Since the optimization criterion does not include pedestrian movements of passengers across the apron, these are not taken into account during optimization. If these pedestrian routes were optimized as a priority, it could result in a much higher number of non-productive airport bus trips (we strive to minimize the use of airport buses to transport passengers around the apron at Ostrava Airport, as this is a non-preferred mode of transport). The total time required for pedestrian movements after solving the model in Equations (1) - (21), was 309 min. Since the total time required for pedestrian movements is one of the important criteria for passenger comfort, it is appropriate to compare the calculated value with the minimum possible value. This is achieved by replacing optimization criterion in Equation (1) with a criterion representing the total time required for walking in Equation (22), namely:

$$\min f(u,v,w,x,y,z,\alpha) = \sum_{i \in I} \sum_{s \in S} d_{is} \cdot w_{is}, \qquad (22)$$

where:

$d_{is}$ The time required for passenger transfers when the aircraft $i \in I$ is assigned to a stand $s \in S$ (This time requirement is calculated as the sum of the time required for passengers to move from the aircraft assigned to a parking stand $s \in S$ o the arrival gate terminal and the time required for passengers to move to the aircraft assigned to a parking stand $s \in S$ from the departure gate terminal).

The results obtained are summarized in Table 4.

***Table 4** Results of a supplementary computational experiment*

| Flight | Assigned stand on the apron | Arrival transfer | Departure transfer |
|---|---|---|---|
| 1 | 1 | by bus | on foot |
| 2 | 5 | on foot | by bus |
| 3 | 3 | on foot | by bus |
| 4 | 1 | by bus | by bus |
| 5 | 5 | by bus | on foot |
| 6 | 3 | by bus | by bus |
| 7 | 2 | on foot | by bus |
| 8 | 4 | by bus | by bus |
| 9 | 2 | on foot | on foot |
| 10 | 4 | on foot | on foot |
| 11 | 2 | on foot | on foot |

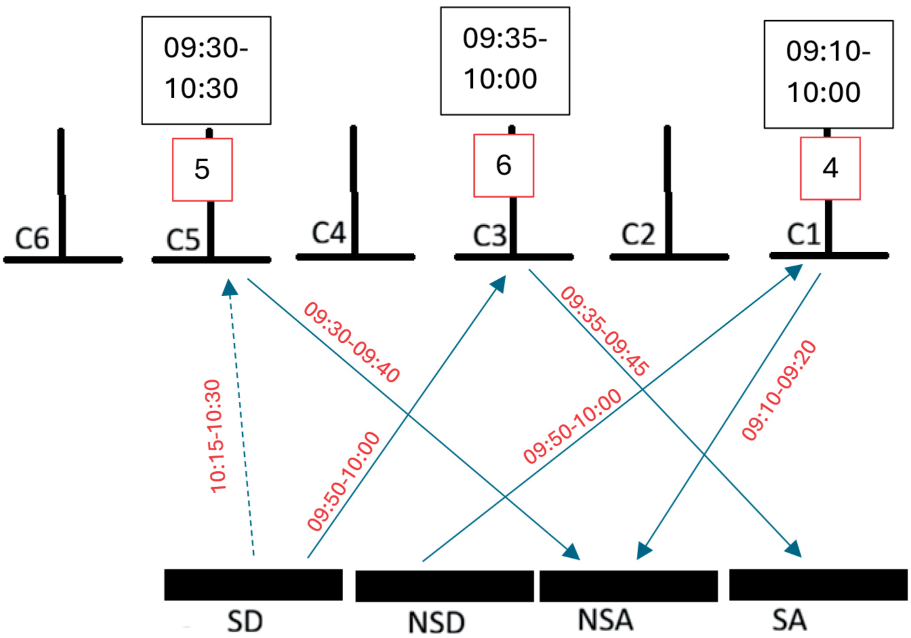


***Figure 2** Analysis of the operational situation during the time period 09:10-10:30 based on the model results in Equations (2) - (22)*

When comparing the total travel times, the use of model in Equations (2) - (21) with optimization criterion in Equation (22) reduced the total travel time for walking trips by 33 minutes to 276 minutes. The calculation took 0.2 seconds. The optimal solution has been achieved.

The solution for the operational scenario during the time period 09:10 - 10:30, when multiple aircraft experience timing conflicts on the apron, is shown in Figure 2.

The dashed line in the image indicates a pedestrian crossing across the apron; the solid line indicates a bus crossing across the apron.

There is no transfer between bus routes here; this means that after completing a route, the bus does not proceed to serve another route but returns to the garage.

When minimizing the value of the optimization criterion in Equation (22), the number of unproductive bus trips increased to 44.

Therefore, the solution to the model in Equations (1) - (21) was implemented repeatedly, with the addition of a constraint ensuring that the optimization criterion in Equations (22) is satisfied at a value of 276 minutes, i.e., a constraint of the form:

$$\sum_{i \in I} \sum_{s \in S} d_{is} \cdot w_{is} \leq 276 . \qquad (23)$$

When the number of unproductive trips was minimized by setting the optimization criterion in Equation (22) to 276 minutes, the number of unproductive trips was reduced to 8.

The results obtained are summarized in Table 5.

The solution to the operational situation between 9:10 and 10:30, when multiple aircraft experience scheduling conflicts on the apron, is illustrated in Figure 3.

The dashed line in the image indicates a pedestrian crossing across the apron; the solid line indicates a bus

***Table 5** Results of the second supplementary computational experiment*

| Flight | Assigned stand on the apron | Arrival transfer | Departure transfer |
|---|---|---|---|
| 1 | 1 | on foot | on foot |
| 2 | 5 | on foot | on foot |
| 3 | 3 | on foot | on foot |
| 4 | 1 | on foot | by bus |
| 5 | 5 | by bus | on foot |
| 6 | 3 | on foot | on foot |
| 7 | 2 | on foot | by bus |
| 8 | 4 | on foot | on foot |
| 9 | 2 | on foot | on foot |
| 10 | 4 | on foot | on foot |
| 11 | 2 | on foot | on foot |

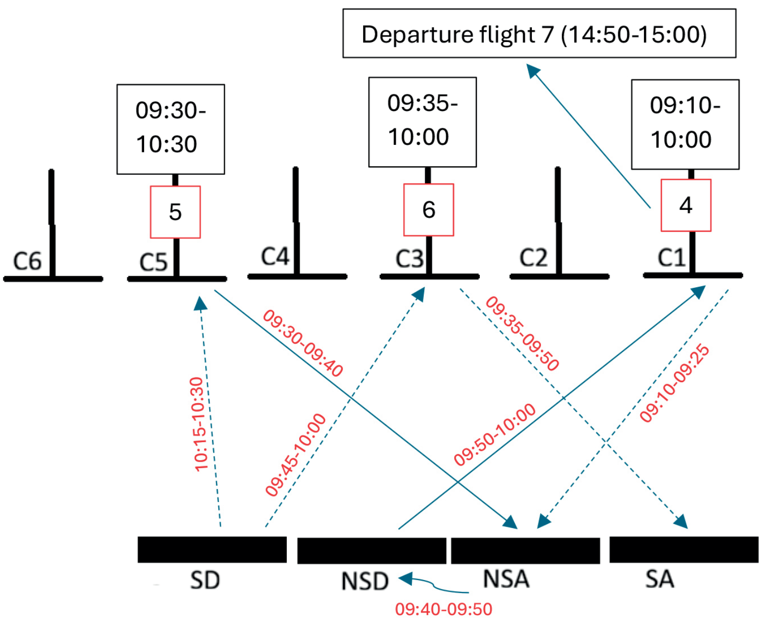


***Figure 3** Resolution of the operational situation during the time period 09:10-10:30 based on the model results in Equations (1) - (21)*

crossing across the apron. The optimal solution has been achieved.

At Ostrava International Regional Airport, for which the model was designed, one gate is always designated for each type of departure (Schengen and non-Schengen) and for each type of arrival (Schengen and non-Schengen). However, there are airports that have multiple gates designated for individual types of departures and arrivals. Some other airports use jet bridges for passenger movement. In such cases, certain airlines (especially network carriers) may require that their aircraft be assigned a parking position equipped with a jet bridge. Other carriers (low-cost carriers), on the other hand, may require that their aircraft be assigned a parking position without a jet bridge. At some airports, for example, passenger movement between the terminal and aircraft on the apron is not permitted for security reasons (transport between parking positions without jet bridges and the terminal is carried out exclusively by buses).

To reduce the number of airport buses used, it is also possible to consider adjusting the time intervals during which passengers may walk across the apron. When making such considerations, however, it is important to bear in mind that adjusting the time intervals for passenger movement on foot across the apron has its limitations, for example, since it may be convenient for passengers to check in within a certain time limit after the aircraft's arrival. Or arriving passengers may request to use public transportation when traveling from the airport (this is limited by the existing bus or train schedule). For example, at Ostrava Airport, trains depart from the airport at 2-hour intervals; during nighttime hours this interval is even longer.

The task of allocating aircraft parking stands can also incorporate the requirement for the movement of handling equipment or the movement of service personnel providing technical handling. It is therefore clear that in real-world operational practice, there are a number of specific factors that the model published in this article does not take into account. Therefore, in further research, we will continue to develop mathematical models so that it is possible to account for the widest possible range of these real-world operational specifics and integrate the aforementioned optimization problem with other optimization problems.

## 5 Conclusion

In this paper is presented a mathematical model for assigning aircraft to apron stands at regional airport where passengers may move either on foot or by airport shuttle buses. Unlike traditional stand assignment approaches, focused mainly on minimizing passenger walking distance or time, the proposed model emphasizes minimizing bus use while preventing conflicts between passenger flows on the apron. This is especially important for regional airports, where buses are usually only a supplementary resource and their availability is limited.

The integer linear programming model combines standard stand assignment constraints with operational and safety requirements related to passenger movement, bus transfers, and stand compatibility. The case study based on real data from Ostrava International Regional Airport confirmed that the model can produce feasible solutions quickly and efficiently. In the tested scenario, the optimal solution required bus transport in only one passenger operation and resulted in just four unproductive bus trips.

The supplementary experiments showed that the selected optimization criterion strongly affects the final solution. Minimizing the walking time improved passenger comfort but led to a significant increase in bus operations, whereas the original model achieved more efficient bus utilization at the expense of slightly longer walking times. This confirms that apron stand allocation is a trade-off between passenger comfort and operational efficiency.

Overall, the model offers a practical decision-support tool for regional airport operations. Its main contribution is the integration of aircraft stand assignment with the coordination of passenger transfers on the apron under safety constraints. Future research may extend the model by including additional operational factors such as handling equipment, staff movements, airline preferences, and multi-criteria optimization.

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**Conflicts of interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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