Airport Gate Assignment problem: Mathematical formulation and resolution

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Abstract—**an efficient flight to gate assignment must ensure the safety of the activities around the parked aircrafts. Knowing that the use of aerobridges is the best solution to minimize the risks associated with operations around aircrafts, increases the revenues of the airport services and reduces the costs of the airline facilities, the maximization of use of aerobridges can be an important objective that could be treated by airport manager. In this work we have treated airport gate assignment problem. We have chosen to implement a multi-objective mathematical model which minimizes the number of un-gated flights and maximizes the use of aerobridges. Some of commonly used constraints such as integrity constraints were used. New operating constraints such as adjacency constraints and the initial gate assignment were studied. The mathematical model was implemented and solved using a multi-stage approach based on the utilization of Cplex Solver. The results, obtained using this approach, were compared to two heuristics commonly used by airport managers. The effectiveness of the implemented approach was illustrated using different test cases generated by a tool that contains a description of the main Tunisian airports. We use probability rules to create different scenarios especially to generate the arrival and departure times.**

Keywords: gate assignment; airport managment; ground optimization; integer programming.

1. INTRODUCTION

Aircraft ground management optimization becomes more and more necessary for airport managers especially with the privatization of airport management activities which gave rise to a competitive environment, the explosion of airport activities covering different types of services and the nature of air transport operations which privilege aircraft safety. That is why effective management of ground management must first ensure the safety of all ground operations while maximizing economic gain without forgetting to take into account operating constraints and the preferences of customers (passengers, airlines, support services, etc.).

Airport ground management can be divided into three main sub-problems specifically the runways allocation sequences optimization, the movement of aircraft on the ground optimization and the optimization of aircraft to gate assignment problem that will make the purpose of this paper. This document is organized as follows. In the first part, we will present an overview of previous works. Then we present our mathematical model, its implementation and experimentation. In the final section, we conclude and introduce an overview of future works.

2. LITERATURE REVIEW

Since the basic gate assignment problem (GAP) is a quadratic assignment problem and was shown to be NP-hard by Obata [1] as mentioned in [2], different solving approaches were developed and can be classified to three main categories. The first is based on mathematical programming techniques, the second on heuristics and meta-heuristics and the last on knowledge based and expert systems.

1) Mathematical programming techniques: they are the most recurrent techniques used to solve the GAP. The problem is usually modeled as constrained allocation problem and models differ in objective functions or constraints taken in consideration. One of the first mathematical models was introduced in [2]. The author introduced a conceptual solution to the aircraft gate assignment problem using 0,1 linear programming model that aims at minimizing the total passenger walking distance and taking into account only single assignment constraints (one aircraft to one and only one gate). This model does not take into account constraints such as physical constraints, neighboring constraints or services preferences constraints, etc.

   The mathematical programming approach proposed in [3] introduced the term "event" defined by the arrival and departure times and type of services applied by the each flight, the objective function is the maximization of the number of events assigned to gates. The author took into account single assignment constraints, occupation constraints and neighboring constraints. The model was solved using a specialized heuristic and tested using some scenarios. The main inconvenience is that this approach does not consider delays or flights cancellations.

   Considering objective functions, different mathematical models were used such as [4] in which the authors aim at minimizing the total transfer passengers distance, [5] in which are integrated costs of delays to minimize intra-terminal travel. In [6], the purpose was to minimize dispersion of idle time periods for the GAP. There are also recent studies which treated real time gates reassignment problem such as [7] in which was defined a mathematical model with a zoning strategy to respond to flight delays;

2) Heuristics and meta-heuristics: to solve the GAP, some heuristics were developed and were sometimes combined with mathematical models. In [8], the authors proposed a heuristic to minimize the total passenger walking distance based on aircraft passenger's number. An aircraft with a larger passenger volume has a higher priority to be assigned to a gate with a smaller average walking distance.

   In [9], the authors implemented a hybrid simulated annealing with Tabu search to solve the GAP. They defined a multi-objective problem in which they minimize the number of flights unassigned to gates and the total walking distance. A greedy algorithm was used to minimize ungated flights and determine the initial solution to be maintained by the main algorithm based on simulated annealing approach. Tabu search was used for some iterations when the number of iterations for which the result is not improved or the neighborhood move is not accepted exceeds a certain value.

   In [10] an approach based on flow network that minimizes both passenger discomfort for transfer connections and fuel burn costs of aircraft taxi was presented. Nodes represent arrival and departure flights and an edge is added if flights represented by corresponding nodes can be assigned to the same gate since their arrival and departure times didn't overlap. The authors implemented an approach based on three level assignments (zone assignment, sub zone assignment and gate assignment). They improved the efficiency of their approach to solve gate assignment problem at the Houston George Bush international Airport (IAH) but this approach can't be generalized to all airports because of different airport configurations around the world.

   Another heuristic approach to solve static and real time GAP was proposed in [11]. It is based on two main stages. At the planning stage, a primary solution is obtained using mathematical model which was solved using CPLEX solver. Then, different flight delay scenarios are introduced, flights are reassigned and penalty values are revised. The process is iterated to obtain a feasible solution.

   In [12], the authors developed four metaheuristics to solve problem formulation introduced in [13]. Among genetic algorithm, simulated annealing, Tabu search and hybrid approach using Tabu search and simulated annealing, Tabu search was improved to be the best among all three classic meta-heuristics. However, the hybrid approach was the best in terms of solution quality and computational time;

3) Knowledge based and expert systems: many expert systems were developed to solve the GAP. The expert system introduced in [14] is composed especially of a database in which are saved different operational data such as flight schedules, number of passengers and amount of baggage connecting with flights, flight movement data, a knowledge base containing airport specifications and procedural knowledge necessary for the inference process and an inference engine based on forward searching rules to determine intermediate conclusions and backward searching rules to determine conditions that must be hold to objectives. This approach improved its ability to solve some close sets of the problem but it is difficult to adapt knowledge to local conditions and changing requirements.

   The expert system developed in [15] aimed at managing gate assignment problem using procedural, declarative and heuristics knowledge which include aircraft ground time services, gate characteristics, capacity needs of individual aircrafts, airport passenger transfer patterns, baggage handling methods and constraints, customer service levels and policies, aircraft service requirements, etc. The inference engine is based on heuristically guided forward chaining inference mechanism.

   The multi-criteria GAP was studied in [16]. The authors introduced a knowledge based airport gate assignment system integrated with multi objective optimization by mathematical programming techniques to provide a solution that satisfies both static and dynamic situations within a reasonable computing time. A partial parallel assignment is introduced. The inference engine considers a group of aircrafts and looks at all the available gates. Then it does the gate assignment by minimizing total waiting delay of all the assigned aircraft, passenger walking distances and baggage handling distances, and maximizing the use of fixed gates.

3. Problem formulation

Using daily airlines programs in which are specified especially arrival times, departure times and type of aircrafts used to perform the flights; the airport manager prepares the flight to gate schedule by assigning all flights to airport gates. In case of unavailability of gates, the airport manager has to solve the problem by clearing flights to another airport or assigning them to a particular area not normally intended to receive aircrafts. The obtained schedule must respect physical constraints such as gate and aircraft characteristics, utilization constraints such as services offered by each gate and temporal constraints imposed by airline programs.

To introduce the mathematical model, let N be the number of aircrafts received at the airport and M the number of gates. In our case we use the same approach used in [9], so we assume that flights which are not assigned to any gate are assigned to a fictitious gate which can accommodate any type of aircraft (gate number M+1) and have an infinite capacity. In response to safety requirements, passenger preferences and flight facilities, we consider the maximization of use of gates equipped with aerobridges. So, we aim at optimizing two objectives: the first is to minimize the number of unassigned flights or flights assigned to the gate number M+1. The second criterion is to maximize the number of aircrafts assigned to gates equipped with aerobridges. The time unit is the minute and the time allocated to an aircraft in a gate is counted from the entry in that gate until its departure and the rehabilitation of the gate (possibly cleaning the area) to be ready to receive a new aircraft. Flights are sorted from one to N by their arriving time and gates are identified by their numbers. To take into account initial gates occupancy, we introduce an initial schedule that can represent existing aircrafts in gates and/or the preference of the airport manager to assign specific flights to defined gates.

Variables that will be used to formulate the problem are as follows:

- N: the number of flights to assign to airport gates during the assignment day;
- N_0 : The number of flights initially assigned;
- M: the number of airport gates;
- M1: the number of airport gates equipped with aerobridges;
- M2=M-M1: the number of airport gates unequipped with aerobridges;
- M+1: fictitious gate. The aircraft assigned to the gate number M+1 is an aircraft for which there is not a valid gate. We suppose that this gate has an unlimited capacity (an unlimited number of aircrafts at the same time) and can accept every type of aircraft;
- A_i : arriving time of flight number i to the airport gate;
- L_i : leaving time of the flight number i from its gate;
- y0 : Initial airport gate assignment;
- $A0_i$: arriving time of flight i for which a gate has been designated beforehand;
- $L0_i$: Scheduled departure time of flight i for which a gate has been designated beforehand;
- $typeA_i$: type of gate requested by the flight number i (1 if the aircraft performing the flight number i can use aerobridge gate, 0 otherwise);
- $typeP_i$: type of gate number i (1 if the gate is equipped with aerobridge, 0 otherwise);
- $C_{i,j} = 1$ If we cannot use gates i and j together, 0 otherwise. This type of constraints is common especially when aerobridges are used. Indeed, for each position of the aerobridge, a new gate is defined but the bridge can be used in only one position at a time;
- $wing_i$: Wingspan of the aircraft performing flight number i.
- $width_k$: Width of the gate k (it corresponds to the wingspan of the largest aircraft for which gate number k was created) ;
- safe_dist: Safety distance between gates. It gives some leeway to aircrafts moving from or to their gates.
- Decision variable $y_{i,k} = 1$ if the aircraft performing flight number i is assigned to gate number k, 0 otherwise;

The mathematical mode_l that we propose to solve is represented by the following optimization formulation (model_1):

Minimize $\sum_{i=1}^{N} y_{i,M+1}$ (1)

Maximize $\sum_{i=1}^{N}\sum_{j=1}^{M} y_{i,j} * typeA_i * typeP_j$ (2)

Under the constraints:

$y_{i,k}.wing_i + 2 * safe_{dist} \leq width_k$
$\forall\ 1 \leq i \leq\ N, \forall 1 \leq k \leq M;$ (3)

$y_{i,k}.typeP_k \leq y_{i,k}.typeA_i\ \ \forall\ 1 \leq i \leq\ N, \forall 1 \leq k \leq M;$ (4)

$\sum_{j=1}^{M+1} y_{i,j} = 1 \qquad \forall i, 1 \leq i \leq N;$ (5)

$C_{k1,k2}.y_{i,k1}.y_{j,k2}(L_j - A_i).(L_i - A_j) \leq 0$
$(\forall i, j, 1 \leq i, j \leq N, i <> j, 1 \leq k1, k2 \leq M)$
(6)

$y_{i,k1}.y0_{j,k2}.(L0_j - A_i).(L_i - A0_j) \leq 0$
$(\forall i, j, 1 \leq i, j \leq N_0, 1 \leq k1, k2 \leq M)$ (7)

$A_i \leq L_i (\forall i, 1\ \leq i \leq N)$ (8)

$y_{i,k} \in \{0,1\} (\forall i, 1\ \leq i \leq N, \forall k, 1\ \leq k \leq M)$ (9)

$typeA_i \in \{0,1\}, typeP_k \in \{0,1\}$
$(\forall i, 1\ \leq i \leq N, \forall k, 1\ \leq k \leq M)$ (10)

$C_{i,j} \in \{0,1\} (\forall i, j1\ \leq i, j \leq M)$ (11)

$A_i, L_i \in [0,1440] (\forall i\ \ 1\ \leq i \leq N)$ (12)

$M = M1 + M2$ (13)

(1) The first objective function: minimizing the number of unassigned aircrafts (or aircrafts assigned to the gate number M+1).

(2) The second objective function: maximizing the number of flights assigned to gates equipped with aerobridges. It should be noted that we are not maximizing occupancy time of aerobridges but the number of aircrafts that use them. This choice allows to the airport manager to take the safety, quality of services and commercial advantages of using gates equipped with aerobridges;

(3) this constraint is related to the ground separation rules and indicates that the gate can't accept any aircraft for which the sum of the wingspan and the safety distance is greater than the gate width;

(4) No aircraft can be assigned to a gate equipped with aerobridge unless it is compatible with services offered by this type of gates ;

(5) Each aircraft is assigned one and only one time to a gate or to the fictitious one;

(6) Two flights assigned to two adjacent gates can't overlap ($C_{i,i} = 1 \; \forall i \; 1 \leq i \leq M$ to indicate that two flights assigned to the same gate can't overlap). This constraint is not applicable to gate number M+1 which can receive many flights at the same time ;

(7) No flight can overlap with a flight assigned to gate by initial airport gate assignment. No flight may overlap with a flight originally assigned to a definite gate. This constraint favors the airport manager's preferences to assign determined flights to specific gates. it can also give the chance to review the real time flight to gate assignment;

(8) Departure time of flight i is greater than its arrival time;

(9), (10), (11), (12) and (13) are integrity constraints.

4. EXPERIMENTATION AND DISCUSSION

Each flight is represented using the following tuple: <flight_number, arrival_time, gate_occupation_duration, preferred_type_of_gate> when:

- The "flight_number" is an automatic sequential number;
- The "arrival_date" is an integer between 0 and 1440 (24x60 minutes) generated using uniform probability distribution. To simulate peak hours, we divide the day into different intervals and in each interval we generate a number of flights proportionally to the real number of flights received by the airport of Tunis Carthage during the specific time period;
- Unlike [17] in which the author assumed that all the flights will leave the airport an hour later after their arrivals, we generate the set of "gate_occupation_duration" using normal distribution with mean equal to 50 minutes and standard deviation equal to 20 minutes;
- The set of "Preferred_type _of_gate" is generated according to aircraft type or model (the Preferred_type_of_gate is equal to one if the aircraft performing the flight is compatible with aerobridge, in other cases it is equal to zero). We note that data related to flights are saved proportionally to their activity at the "Tunis Carthage airport" and we use a uniform distribution to choose one flight for each generated flight to guarantee a representative simulation.

To solve GAP formulated below and because of lack of experimental data, we used C++ to implement an application in order to generate different scenarios. The application contains a database in which are saved aircrafts characteristics classified by their constructors and their models. The airport data obtained from Tunisian Aeronautical Information Publications are also saved in the same database. We used two instances of airports:

- The first instance is composed by 10 gates from which 4 are equipped with aerobridges. All of them can be used simultaneously;
- The second instance represents Tunis Carthage airport which is composed by 49 gates, 11 of them are equipped with aerobridges from which only 5 can be used simultaneously because of adjacency constraints.

The initial schedule is performed by a random assignment of little number of flights (N0<10) to gates. Different problem sizes (N=10, N=100, N=200, N=300) and arrival times (5, 10, 20, 30 arriving flights during the rush hour) configurations were considered.

After data generation, the simulation context is saved into a data file. Because of non-linear feature of our mathematical model, we use Cplex 12.4 CP Optimizer to determine a feasible flight to gate assignment. We consider that a solution is feasible if all the flights are assigned to gates and an optimal solution is found if all the flights are assigned to gates equipped with aerobridges

Since solving of mono-criterion optimization problems is simpler than solving multi-criteria problems and in order to guarantee that all the flights will be allowed to land at the airport, we opt for a two-stages-solving approach:

- The 1st stage: we solve the "Model_2" defined by the model_1 without taking into account the second criterion. This step allows us to decide if the airport is able to receive all the flights generated (there is an optimal assignment or $\sum_{i=1}^{N} y_{i,M+1} = 0$). If the airport can't accept all flights, we modify experimental data by removing some flights. We consider that there is not a feasible solution if computation time exceeds one hour or the computer crashes ;
- The 2nd stage: after preparing experimental data, model_1 is modified as follows: the first criterion is not considered and constraint (5) is replaced with the following constraint (5')

$$\sum_{j=1}^{M} y_{i,j} = 1 \quad \forall i, 1 \leq i \leq N; \; (5')$$

In addition to the solving approach using Cplex Solver, the two following sequential assignment heuristics were implemented:

1. First unused gate assignment (FUGA) heuristic: The flights are sorted by their arrival times and the gates

by their numbers (the first M1 gates are those equipped with aerobridges). For each new flight, we start by testing if the first gate can receive the considered flight. If a flight can't be assigned to gate number i, we consider the (i+1)th gate. The process is repeated for all the flights. In addition to favoring the utilization of gates equipped with aerobridges. This approach defines airport manager's preferences to use some specific gates which are considered more beneficial ;

2. Most Unused Gate Assignment (MUGA) heuristic: in this case, the flights are also sorted using the same rule as before. But the gates are sorted in the ascending order of their occupancy frequencies (number of flights accepted by each gate). For each new flight, the gates are reordered by their occupancy frequencies and those equipped with aerobridges are placed in the first M1 positions. The assignment process is the same as that used in FUGA.

The following results were obtained using a personnel computer with i5 (2.4 GHz) processor and RAM of 6 Go:

1. 1st instance of airport :

    - For problems of small sizes (figure 1), the two-stages-solving approach, FUGA and MUGA heuristics find solutions that assign all the flights to gates. But the two-stages-solving approach finds solutions that are better in term of maximizing the use of aerobridges ;
    - if there is no feasible solution generated by the first stage of the two-stages-solving approach, both of FUGA and MUGA heuristics don't find any feasible solution;
    - For all instances, the solution found by the two-stages-solving approach is better than solutions found by FUGA and MUGA;
    - If a feasible solution is found, the computing time spent in FUGA and MUGA heuristics is of the order of a few seconds. For the two-stages-solving approach, Computing time is about few seconds for simple configurations (N<100 and a maximum of 10 arriving flights in the rush hours). For more complex configurations (N=300 and more than 25 arriving flights in the rush hours), computing time becomes more important. But, solutions given by the two-stages-solving approach are better in term of maximizing the use of aerobridges (16 flights from 32 are assigned to aerobridges)

2. 2nd instance of airport:

    - For problems of small sizes, the two-stages-solving approach, FUGA and MUGA heuristics find solutions that assign all the flights to gates. But the two-stages-solving approach finds solutions that are better in term of maximizing the use of aerobridges;
    - For more complex configurations (more than 25 arriving flights in the rush hours), the two stage approach doesn't find any solution because of lack of memory. The two heuristics find feasible solutions which are not always optimal.

```
! ----------------------------------------------------------------------------
! Minimization problem - 25 variables, 545 constraints
! Initial process time : 0,00s (0,00s extraction + 0,00s propagation)
!  . Log search space  : 775,0 (before), 16,0 (after)
!  . Memory usage      : 731,9 kB (before), 747,9 kB (after)
!  . Variables fixed   : 9
! Using parallel search with 4 workers.
! ----------------------------------------------------------------------------
!          Best Branches  Non-fixed    W       Branch decision
*             0       6 0,04s        1              -
! ----------------------------------------------------------------------------
! Search terminated normally, 1 solution found.
! Best objective         : 0 (optimal - effective tol. is 0)
! Number of branches     : 881
! Number of fails        : 372
! Total memory usage     : 4,4 MB (4,1 MB CP Optimizer + 0,3 MB Concert)
! Time spent in solve    : 0,04s (0,04s engine + 0,00s extraction)
! Search speed (br. / s) : 18 824,7
! ----------------------------------------------------------------------------
```

Figure 1: test case using 5 arrival flights during the rush hour (first stage)

```
! ----------------------------------------------------------------------------
! Search terminated normally, 5 solutions found.
! Best objective         : 1 (optimal - effective tol. is 0)
! Number of branches     : 171 712
! Number of fails        : 73 127
! Total memory usage     : 392,3 MB (386,2 MB CP Optimizer + 6,1 MB Concert)
! Time spent in solve    : 69,15s (69,15s engine + 0,00s extraction)
! Search speed (br. / s) : 2 483,0
! ----------------------------------------------------------------------------
```

Figure 2: test case using 33 arrival flights during the rush hour (first stage)

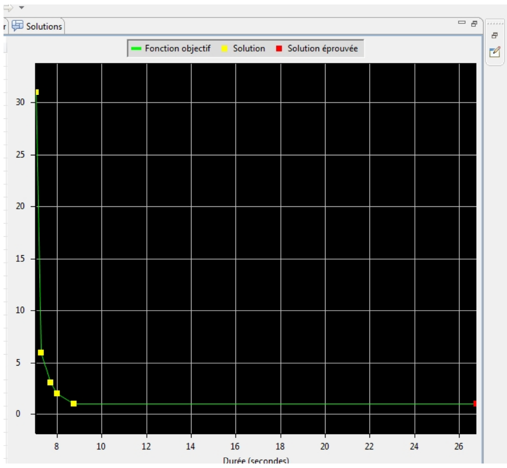

Figure 3_1: test case using 33 arrival flights during the rush hour (first stage)

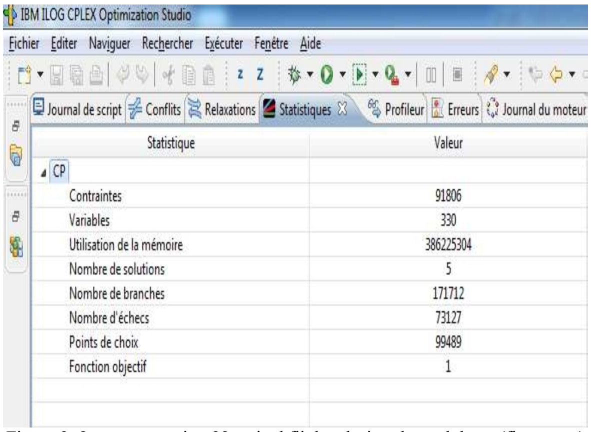

Figure 3_2: test case using 33 arrival flights during the rush hour (first stage)

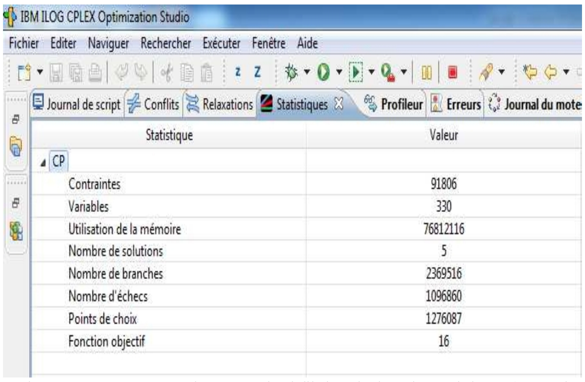

Figure 4_1: test case using 33 arrival flights during the rush hour (second stage)

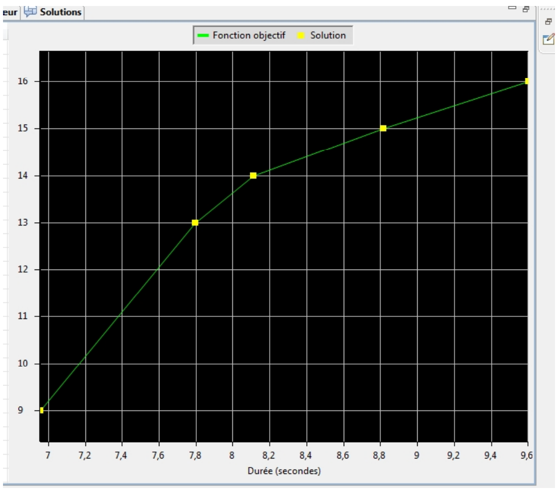

Figure 4_2: test case using 33 arrival flights during the rush hour (second stage)

5. Conclusion

In this paper, we introduced a multi-criteria optimization model. The first criterion is considered the most popular criterion in the literature, but the optimization of aerobridge utilization is not widespread. We introduced this criterion because of benefits that are offered by aerobridges especially in term of safety of ground aircrafts moves. A two-stages-solving approach was performed. The first stage is used to determine if the airport can receive all the flights. In the second stage we use problems for which there is at least one feasible solution and maximize the aerobridge utilization. The initial gate assignment is also integrated in the mathematical model.

We also have implemented two simple heuristics that are used by airport managers to perform daily flights to gates schedules. These two heuristics have proven their performance for problems of small and medium sizes. But for more complex problems, the use of FUGA or MUGA heuristics is much less efficient than the use of the multi-stage-solving approach especially when maximizing the use of aerobridges. For configurations with important number of aircrafts and gates, the two stages approach is unable to find any solution even for problems that can be solved using simple heuristics. This shows the limitation of deterministic approaches against the problems of large size and leads us to consider approximate methods.

Only the problems for which a feasible solution exists have been solved by the second stage. This choice is proven by the loss that can be engendered by the refusal of landing. A study which aims at combining the two criteria while highlighting the importance of receiving all flights can be conducted.

In our formulation, we tried to introduce a simple mathematical model which takes into account the main operating constraints such as adjacency constraints and initial gate assignment which are not widespread in literature. Some other constraints related mainly to the handling services are not treated in literature and could be considered in further works.

To validate the implemented solution, we used a simulation approach and we generated different scenarios. This approach helps to identify the airport capacity and to simulate critical situations. However, a study based on real data can be conducted to improve our approach.

The main inconvenient of maximizing the utilization of aerobridges is that they are usually installed in the same apron and we can't optimize their utilization without optimizing the ground circulation around them. A global approach which treats the problem of ground activities optimization can be studied and performed with real data.

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