**Scheduling Aircraft Landings – The Static Case**

Cátia Teixeira, Sónia Ferreira and Vasco Bartolomeu

Master’s degree in Data Science & Engineering, Faculty of Engineering - University of Porto

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**Abstract:** This paper presents the problem of Scheduling Aircraft Landings, an important practical problem in today's world, as the industry suffered an overall tremendous growth in the past decades, and in many countries, effective use must be made of the available runway capacity. The problem consists of determining how to land aircraft approaching an airport and involves assigning each aircraft to an appropriate runway, by computing a landing sequence for each runway and scheduling the landing time for each aircraft. The main objective is to achieve effective runway use. For this purpose, the Aircraft Landing problem is considered. Two techniques will be presented: Mixed Integer Programming and Constraint programming. Computational results are then presented comparing the two techniques used and for tests using …**FINISH/COMPLETE/CHANGE**

**Keywords:** Aircraft landing scheduling, Delay minimization, sequence-dependent scheduling, Runway operation, Mixed integer programming, Constraint programming.

# Introduction

Over the past few decades, air traffic has experienced tremendous growth, as air transport become one of the fundamental modes of transport for personal and business travel, and commercial delivery. However, in 2020 due to the worldwide COVID pandemic (that started that same year), the industry observed a setback in their numbers, with less traffic for passengers and freight traffic their growth has dropped tremendously [1]. In the next year (2021) the numbers rose to show an improvement from 2020, but they are still very far away from the pre-pandemic numbers [2].

As air traffic developed, the limitation of resources, like manpower but special the limitation of runways become a bottleneck during airport operations. Located in Europe, London Heathrow airport is one of the busiest airports in the world and has only two runawys. When the number of approaching flights overpasses the airport capacity, some of these aircraft can’t be landed on their “target” landing time. Resulting in an extra cost mainly on a waste of fuel for each plane flying faster than its most economical speed. Airlines will have to deal also with costs for delays of their fights and unsatisfied customers. Transfer customers can miss their connecting flights. The crew operating the current flight can be needed on another flight, which has now to be rescheduled resulting in another extra cost. Flights that are on land (departing flights) can also be affected by this, as they can also be delayed and not authorized to depart due to the lack of available runways, this will also have an impact on the operations of the destination airport of these flights. Other possible costs are crew overtime payments, crew rescheduling, etc. Back in 2017, it was reported that congestion cost to airlines and passengers around 25 billion euros, according to FAA/Nextor estimated [3].

Therefore, even now that the air industry is not growing or even having the same results as in past years it's important to solve the problem of scheduling aircraft landings which is referred to as the Aircraft Landing Problem (ALP) in the literature. APL consists of the problem of assigning each aircraft an optimal landing time and runway in a way that the cost is minimized. This can be achieved by reaching the maximum efficiency of resources and overcoming the problems observed in the past decades when the increase in air traffic causes a drastic increase in the number of aircraft take-offs and landings within a given period at a certain airport or runway, that results in an overload issue in terms of airport capacity and delay issue in terms of aircraft scheduling.

Air traffic control (ATC) aims to control air traffic, to prevent collisions and delays. ATC is usually operated by humans and therefore human error can happen. An important part of their responsibility is the planning of airport operations, such as the arrival and departure of aircraft, which is the focus of this paper. Automating this solution, will not only save time but overcome human error.

Aircraft landing scheduling can be understood as giving priority to different aircraft, that need to land at a certain time. This problem becomes more complex, as previously explained, in busy airports with limited runways and with several aircraft trying to land at the same period.

But there are different ways of formulating this problem, depending on the perspective used. For instance, from a point of view of an airline, their main objective would be to minimize the deviation from the “target” landing time, while from an airport management perspective is to maximize the airport capacity usage and therefore minimize their cost in losses. Both objectives are directly related to cost and the final objective is to minimize direct and indirect costs associated with aircraft landing for both airliners and airport managers.

In resume, air transportation has established itself as one of the most important means of transport, which directly implies the increase in air traffic, and therefore the efficient management and scheduling of aircraft take-offs and landings (given the limited resources such as time, budget, etc..) have become a very challenging and complex problem for air traffic controllers.

Therefore, this paper, it will be considered the problem of scheduling aircraft landings at a given airport for multiple runway airports. The problem is considering a landing time on a runway for each plane for a given set of planes such that:

* each plane lands on the predefined window.
* separation criteria between the landing of a plane, and the landing of all successive planes, is respected.

Mixed Integer Programming and Constraint programming will be used to address the problem, formulating this from the point of view of airport management. The main goal is to find an optimal landing sequence based on the available runways, number of flights, and expected delays and therefore minimize their cost.

The organization of the paper is as follows. In section 2, an overview of the problem context is given. In section 3, … In section 6, the results obtained in sections 4 and 5 are discussed.

In section 7, the paper is concluded. **FINISH/COMPLETE/CHANGE**

The aircraft scheduling problem has been widely studied in the operation research community, and therefore this research will adopt its foundation paper “Scheduling Aircraft Landings—The Static Case” by J.E. Beasley, M. Krishnamoorthy, Y.M. Sharaiha and D. Abramson [4].

As in their study, is important to refer that through our paper we will typically refer to planes landing, but the models presented can be applied to problems involving just takeoffs or to problems involving a mix of landing and takeoffs on the same runway. Also, we are dealing only with the static case, where we have all the knowledge about the set of planes that are going to land and no information (i.e. planes land, new planes appear, etc) changes.

# Problem Context

Air traffic control will give instructions to each aircraft entering within the range of an airport radar. A landing time and a runway will be assigned to each plane. The landing time must be comprehended between the earliest landing time and the latest landing time.

The earliest landing time corresponds to the time at which the aircraft can land if it flies at its fastest speed, and the latest time corresponds to the maximum landing time achievable considering delaying mechanisms, such as decreasing the speed of the plane, or if the flight plan can be lengthened by circling. Comprehended in this time window there is the target time that corresponds to the time at which the aircraft can land if it flies at its cruise speed. This is considered the preferred landing time (target landing time).

To ensure safety is necessary to ensure that separation distances are respected. Separation distances are converted into separation times using a fixed landing speed that will be different according to the type of aircraft that is landing. After this, a minimal lapse of time between the landing of a plane and the landing of any successive plane needs to be ensured. Separation time holds between a pair of planes landing on the same runway or on different runways.

In resume, the Aircraft Landing Problem (ALP), concerns the scheduling of planes at an airport by assigning to each plane a runway and a landing time that falls within the specific time window and does not violate the safety constraint (separation time) in a way that the cost is minimized. When it’s not possible to land the plane at the target landing time, the plane can be landed at any time that falls between the early and the late landing time, but this will incur a cost (penalty cost).

Therefore, the objective function, considered in this study is the minimization of the total cost associated with landing planes at times that differ from the target landing time, for the static case in a multiple-runway airport.

# Problem Formulation

In this section (for conciseness) we will formulate the multi-runway ALP problem to minimize the cost adopted from [4]:

The notation is as follows:

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| --- | --- |
| *P* | number of planes |
| *Ei* | the earliest landing time for plane i (i=1, … , P) |
| *Li* | the latest landing time for plane i (i=1, … , P) |
| *Ti* | the target (preferred) landing time for plane I (i=1, … , P) |
| *Sij* | the required separation time (≥ 0) between plane i landing and plane j landing (where plane i lands before plane j), i=1,...,P; j=1,...,P; i≠j |
| *gi* | *be the penalty cost (≥ 0) per unit of time for landing before the target time Ti for plane i (i=1,...,P)* |
| h*i* | *be the penalty cost (≥ 0) per unit of time for landing after the target time Ti for plane i (i=1,...,P)* |

The decision variables are:

|  |  |
| --- | --- |
| *xi* | *the landing time for plane i (i=1,...,P)* |
| *αi* | *how soon plane i (i=1,...,P) lands before Ti* |
| *βi* | *how soon plane i (i=1,...,P) lands after Ti* |
| *δij* | *1 if plane i lands before plane j (i=1,...,P; j=1,...,P; i≠j)*  *0 otherwise* |

Due to security concerns, is extremely important to ensure that the separation constraint between landings is satisfied. Because although sometimes for a certain pair (i, j) of planes it’s possible to observe clearly if δij = 1 or δji = 1. However, knowing the order in which a set of planes should land doesn’t mean that the separation constraint is automatically fulfilled.

Therefore, three sets were defined:

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| --- | --- |
| U | the set of pairs (i,j) of planes for which we are uncertain whether plane i lands before plane j or not |
| V | the set of pairs (i,j) of planes for which i definitely lands before j (but for which the separation constraint is not automatically satisfied) |
| W | the set of pairs (i,j) of planes for which i definitely lands before j (and for which the separation constraint is automatically satisfied) |

Objective Function:

Subject to (constraints):

The objective function (1) will minimize the total costs of deviation from the target times (Ti).

Constraints (2) ensure that the scheduled landing time for each aircraft lies within its time window. Constraints (3) ensure that aircraft i will land before aircraft j (δij = 1) or aircraft j lands before aircraft i (δji = 1). Constraints (4) represent the pairs of planes (i, j) for which i lands before j ad for which is not always guaranteed that the separation constraint is always satisfied (union of set W and V). Constraints (5) ensure a separation constraint for the pairs of planes in U. Constraints (6) and (7) ensure that αi is at least as big as zero and the time diﬀerence between Ti and xi, and at most the time diﬀerence between Ti and Ei. Constraints (8) and (9) are similar equations for βi. Constraints (10) relate the landing time (xi) to the time plane i lands before (αi), or after (βi), target (Ti). Constraints (11) ensure that each plane lands on exactly one runway whereas constraints (12) are symmetry constraints (meaning that, if i and j land on the same runway so do j and i). Constraints (13) ensure that, if there is any runway r on which plane i and j are both landed (i.e. yir = yjr = 1), then we force zij to be 1 (i and j land on the same runway). If zij = 0, then constraints (13) become 0 ≥ yir + yjr − 1, ensuring that planes i and j cannot land on the same runway. Constraints (14) and (15) fulfill the requirement that the separation time is Sij for planes landing on the same runway but sij for planes landing on different runways can be easily dealt with it, for set V and U respectively.

The formulation described above will be used in the MIP and CP models.

# The Models

The proposed formulation is implemented and solved via Docplex, the Python API of CPLEX solver. The test problem instances are generated from the data obtained from OR-Library [5]

## MIP Model

## CP Model

# Computational Results

An analysis of the tests and results (including some KPIs on the difficulty of the instances and resolution time)

As previously stated, both algorithms were implemented and solved via Docplex, the Python API of CPLEX solver. Using instances generated from data obtained from OR-Library [5].

Each test problem was conducted by

# Conclusions

An approach to scheduling the landing of aircraft based on mixed integer programming (MIP) and constraint programming (CP) was introduced. The proposed formulation considers the multiple runway problem for the static case. Computational results were presented for several test problems involving up to 1409 planes and two runways.

As the formulation of the MIP model advanced into the final formulation, was possible to observe a shift in the results as the formulation gained more strength by the introduction of all the constraints recommended in the adopted paper [4].

Computational results indicate that

By modeling the CP model accordingly to the initial formulation of the MIP model, it was possible to observe that the CP model execution was not efficient. Therefore another formulation for the CP model was attemped….

# Future Research

As a result of the work conducted in this paper, the following future research is suggested:

* Investigation of the dynamic case of ALP

The research in this paper focused on the static case of the ALP. This can be an interesting way of investigating and planning the airport's runway capacity in a strategic planning stage. Nevertheless, in the day-to-day operations, the information on the landings, such as the earliest, target, and latest time might change. Therefore, a dynamic approach seems a crucial next step.

* Investigation of the single runway formulation of ALP for the static case and dynamic case

Most of the busiest international airports have at least two runways but can have more. Therefore, for this initial study efforts were made to approach this formulation that can affect a wide range of airports and deal with different types of problems (i.e. different types of planes, overlapping landings, runway unavailability, …). Nevertheless, the single runway formulation should also be investigated since it will cover a range of airports not covered in this paper, allowing improvement in the airport's runway capacity for the strategic planning stage in the static case and the day-to-day operations in the case of the dynamic case.

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