# SESAR Engage KTN – PhD final report

| | |
|---|---|
| PhD title: | Second generation Agent-Based modelling for improving APOC operation |
| Candidate's name: | Olivia Sashiko Shirai Reyna |
| Lead supervisor's name: | Daniel Delahaye |
| Co-supervisor's name (if applicable): | Miguel Mujica Mota |
| Proponent institute: | Amsterdam University of Applied Sciences |
| Consortium institutes (if applicable): | Ecole Nationale de l'Aviation Civile (ENAC) |
| Thematic challenge: | TC4 Novel and more effective allocation markets in ATM |
| Edition date: | 13 July 2022 |
| Edition: | 1.1 |
| Dissemination level: | Public |



This project has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 783287.

# 1. Abstract

The main objective of this work is to create a Decision Support Tool to help the Airport Operation Centre with the integration of different approaches at the macroscopic level to make better decisions to minimize airport congestion by mitigating conflicts of critical resources. The main conflicts are related to different processes of the airport management and the capacity, so, the main problems are related to the minimum separation, runway, taxiway, terminal, gates, and ground handling team capacity (overloads) and availability.

We propose a framework as part of the Decision Support Tool to solve the conflicts addressed, we adapted an optimization with simulated annealing heuristic combined with a time decomposition approach (sliding windows).

As part of the solution, we evaluate the performance of the different modules and how the number of conflicts is solved, the final objective is to improve the coordination and efficiency of the operations of an airport. To validate the optimization model and to show the benefits of the macroscopic decomposition approach different computational experiments were performed with real data of one day of operations from Paris Charles de Gaulle airport including the parameters of this airport.

# 2. Objective of the study

The objective of our work is to develop a Decision Support Tool to help the APOC processes, this with the integration of the AMAN, SMAN and DMAN with the ground handling optimization considering the gate assignment problem and solve the conflicts related to capacity and airport and airspace constraints.

# 3. Motivation

The concept of Total Airport Management (TAM) developed by EUROCONTROL and the German aviation research institute DLR, widens the scope of A-CDM (Airport Collaborative Decision Making) in both the level of detail and space [Günther, Inard, Werther, Bonnier, Spies, Marsden, Temme, Böhme, Lane and Niederstraßer (2006)].

The TAM has different blocks:

- APOC (Airport Operation Centre) - Manage performance;
- AOP (Airport Operation Plan) - Monitor performance;
- MET (Meteorological Services) - Integration of data;
- DCB (Demand capacity Balancing) - Arrive and depart to plan;
- Integration of landside processes;
- Integration of de-icing processes.

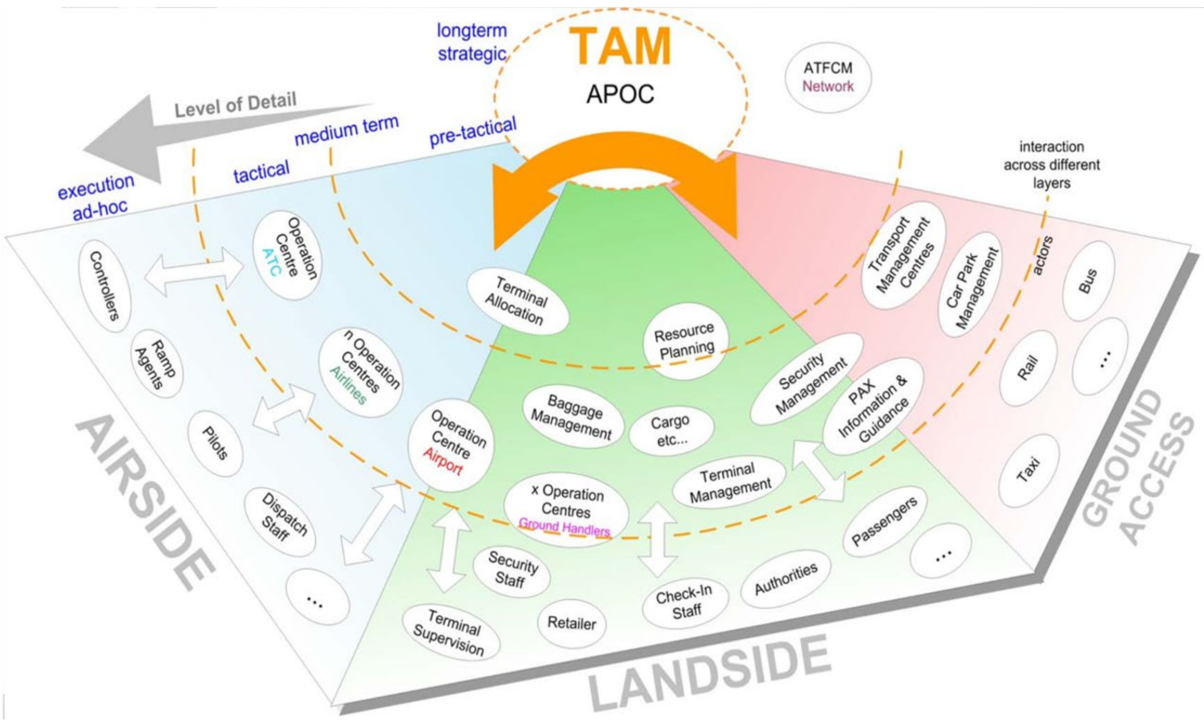


*Figure 1 Total Airport Management (TAM). Holistic View of the TAM and APOC.*

This widening of the scope of the TAM is visualized in Figure 1. At the centre of this concept lies the Airport Operation Centre (APOC). The APOC combines all relevant information of the airports access systems, land and air side traffic, ground operations and weather conditions. This data enables continuous monitoring of the joint plan, the Airport Operations Plan (AOP), and enables better detection/anticipation of deviations.

SESAR's Airport Operations Centre (APOC) [EUROCONTROL (2018)] concept represents a big step forward for airports, providing them with the means to integrate even more efficiently into the European network in a collaborative approach that involves all actors (airport operators, airport coordinators, airlines, air navigation service providers), operating at each airport in a harmonized approach. However, while the APOC idea is considered a must-have for bigger airports, not every airport is likely to establish an APOC physically, as not all airports have the local scope and/or size to justify such an investment.

The SESAR concept envisions the APOC as the central node in the holistic approach of the airport, combining information to manage all airport processes both on the apron and in the terminal. All actors that have operations at and around airports increasingly recognise the need for transparent and collaborative processes and sharing of information.

The main characteristics for an APOC are:

- Including all airside and landside processes (terminal and apron);
- Continuous data sharing amongst all partners;
- Planning and simulation tools to support decision-making.

For an APOC to succeed, the following should be unconditional:

- The role and function of an APOC should be agreed upon;
- (Live) Data sharing between all stakeholders;

- Planning and simulation tools should have been proven trustworthy.

The main objective of this work is to minimize airport congestion by mitigating conflicts for critical resources. The main conflicts are related to minimum separation violations, runway, taxiway, terminal, gate capacities and ground handling team availability. Thus, we developed an efficient Decision Support Tool for managing the traffic and capacity of an airport. The main issue, for most of the models of airport operations present in literature, is that they do not consider the variability of the real system. Therefore, the solutions, when applied to real conditions, are very rigid and can become unfeasible due to the disturbances of the real system. With the objective of making the solutions more resilient and applicable, the uncertainty coming from real-world conditions is considered in this approach.

The problem consists of building a Decision Support Tool for APOC stakeholders with the integration of airspace, airside operations and the decisions taken on the tactical phase (day of operations). Airspace operations involve landing sequencing while airside operations involve runway, taxiway, terminal operations, and ground handling operations. The objective, regarding the landing sequencing, is to resolve airspace conflicts and have a smooth arrival flow of aircraft. Regarding airside operations, the objective is to regulate the departure rate aiming at mitigating the congestion at the airport surface.

In terminal airspace TMA (Terminal Manoeuvring Area) [Ma et al. (2019a)], aircraft from different entry points must be merged and sequenced into an orderly stream, follow the Standard Terminal Arrival Routes (STAR), then prepare to land on the runway. After landing and exiting the runway, aircraft taxi towards the assigned gate. Then, after a certain turnaround duration for disembark, embark and other ground handling operations assigned to the different ground handling teams (arrival and departure), aircraft pushback, taxi out, depart, and follow the designated Standard Instrument Departure (SID) routes.

The first step is to consider the terminal and airport integration problem at a macroscopic level, to be sufficiently flexible to resolve airspace conflicts, to mitigate airport congestions and to ensure feasibility. The second step is to analyse the gate assignment and the ground handling teams assignment.

The ground handling team assignment problem is related to the set of teams that are assigned to the flight depending on the availability, wake turbulence category, distance, and service time.

The main conflicts or overload detection for each phase of the processes are described as follow:

- Airspace: Aircraft incur conflicts every time a loss of minimum separation between two consecutive aircraft is detected. Aircraft that do not respect the order of the sequence along the landing route.
- Airside: Airside conflicts are detected, for terminal components, when their declared capacity is exceeded (capacity overload). For taxiway system the conflicts are detected when the interaction between different the taxiway routes, runway crossing and the incoming/outcoming to the apron.

- Runway: Runway overload is computed by a maximum throughput (number of aircraft per 10 minutes time period).
- Gates: The gate conflicts are detected when two (or more) aircraft used the same gate at the same time.
- Ground Handling Teams: GH team issues happen when the GH schedule ends with a default of service for an aircraft (the service has not been given to the aircraft).

# 4. Advances this work has provided with regard to the state of the art

Some researchers [Kjenstad, Mannino, Nordlander, Schittekat and Smedsrud (2013)] made a mathematical model that integrates the three problems (AMAN, DMAN, SMAN) and the algorithm decomposes the problem where routing, sequencing, and conflicts resolution are carried out in subsequent stages. Their optimization approach on departure management and surface routing has been validated in experiment on Hamburg airport, where they showed remarkable improvements in punctuality and taxi times compared to the expert controllers. There is another case study [Pavese, Bruglieri, Rolando and Careri (2017)] of DMAN-SMAN-AMAN optimization applied to Milano Linate airport. This work has been tested on two actual case-study days, considering the airport stakeholders' objectives and constraints, and taking operation information from the Airport Collaborative Decision-Making platform. Obtained results show that the proposed algorithm could increase average timeliness, reduce taxi time, and fuel consumption of aircraft operating at Linate, thus contributing to reach a more sustainable and efficient air transport.

Our research is an extension from previous works made by Ji Ma [Ma, Delahaye, Sbihi and Mongeau (2016a), Ma, Delahaye, Sbihi, Scala and Mota (2017a), Ma, Delahaye, Sbihi, Scala and Mota (2019a), Ma, Delahaye, Sbihi and Scala (2018), Ma, Delahaye, Sbihi and Mongeau (2016b), Ma, Sbihi and Delahaye (2019b), Scala, Mujica Mota, Ma and Delahaye (2020), Scala, Mujica, Delahaye and Ma (2019)] where AMAN and DMAN are integrated to solve the case of Paris Charles de Gaulle Airport. These papers present the algorithmic implementations of a decision support system for solving airspace conflicts and airport congestion at a macroscopic level. Conflict detection and resolution methods are applied on predefined terminal route structure. Different airside components are modelled using network abstraction. Speed, time, and runway changes are managed via an optimization methodology. An adapted simulated annealing heuristic combined with a time decomposition approach has been proposed to solve the corresponding problem. The system developed provide support for air traffic controllers in handling large number of flights while solving conflicts. In this framework, airspace together with ground airport operations are considered. Conflicts are defined as separation minimum violation between aircraft for airspace and runways, and as capacity overloads for taxiway network and terminals. The methodology proposed in this work consists of an iterative approach that couple's optimization and simulation to find solutions that are resilient to perturbations due to the uncertainty present in different phases of the arrival and departure process. An optimization model was employed to find a (quasi)optimal solution while a discrete event-based simulation model evaluated the objective function. By coupling simulation with optimization, they generate more robust solutions resilient to variability in the operations.

On the other hand, there are a couple of research related to the ground handling optimization. The main goal of this research [Szabo Pilat, Makó, Korba, Čičváková and Kmec (2021)] is to improve the individual processes that are part of the aircraft ground handling to speed up the operation, as well as to improve the turnaround time between individual flights to enhance the overall throughput of airport stands. The objective of this research is to measure the times of standard airport processes that are part of the aircraft handling, to measure the turnaround time between individual flights at the selected airport and to increase the efficiency of each process that was measured. The changes were mainly focused on the following aspects: the position of ground handling equipment before the arrival of the aircraft, the deployment of staff, and the routes taken by ground handling equipment. After the changes were implemented, the same measurements were taken again to see if the changes that had been implemented could speed up the overall process of the aircraft ground handling. All measurements were done at the Kosice airport. This paper also gives us an overview of the number of employees required for each ground handling processes.

This article [Jan Evler (2021)] studies a concept which incorporates the situational awareness gained by A-CDM into an airline-internal decision support system, such that it integrates all available schedule recovery options during aircraft ground operations. The developed mathematical optimization model is an adaptation of the Resource-Constrained Project Scheduling Problem (RCPSP) and incorporates key features from turnaround target time prediction, passenger connection management, tactical stand allocation and ground service vehicle routing into the airline hub control problem. The model is applied in a case study consisting of 20 turnarounds during a morning peak at Frankfurt airport. Schedule recovery performance (resilience) is analysed for a set of key performance indicators within multiple scenario instances which contain different resource availability and aim at solving various arrival delay situations. Results highlight that a minimization of tactical cost concurrently reduces the average departure delay for flight and passengers while recovery performance is substantially affected when some options are not included in the evaluation process. Their concept provides airlines with an optimization approach for constrained airport resources so, that total cost and delay resulting from schedule deviations are reduced, which may benefit to the strategic schedule planning and improve predictability of operations for local collaborators, such as airport, ground handlers and ATM performance.

The integration of optimization support systems to act as holistic decision-support tools for all airport partners. Several integrated problems have been defined and studied in the literature. In some research [Lee and Balakrishnan (2012), Deau, Gotteland and Durand (2009)], taxiway and runway schedules are optimized, and ground traffic simulations carried out to compare with the optimization results. In [Khadilkar Harshad (2016)], a paradigm for the management of aircraft operations in and around airports is proposed to reduce congestion on the airport surface and in arrival airspace.

The objective of our work is to develop a decision support tool that integrate the AMAN, SMAN and DMAN with the ground handling optimization considering the gate assignment problem considering some operational restrictions and airport resources constraints. This full integrated optimization has not been studied before.

## 5. Methodology

In this section we will introduce different aspects that we consider, and we present the methodology followed. We begin the methodology by providing a brief description of the airport that we will focus the study on, which is Paris Charles de Gaulle CDG, then we introduce the network model representation develop for CDG airport taking into a count the different agents. The mathematical model was built with the different variables and parameters. The decision variables were defined. To complete the mathematical model, we develop the objective function with the overloads of terminals, gates, ground handling teams, taxiway, and flight delays.

### Airport model

Paris Charles de Gaulle (CDG) airport is one of the busiest passenger airports in Europe, also consider as a hub airport, composed of four parallel runways (two for arrivals and two for departures) and three terminals.

We choose to study Paris CDG airport because of its complexity and accessibility to the data. Figure 2 represents the airport infrastructure.

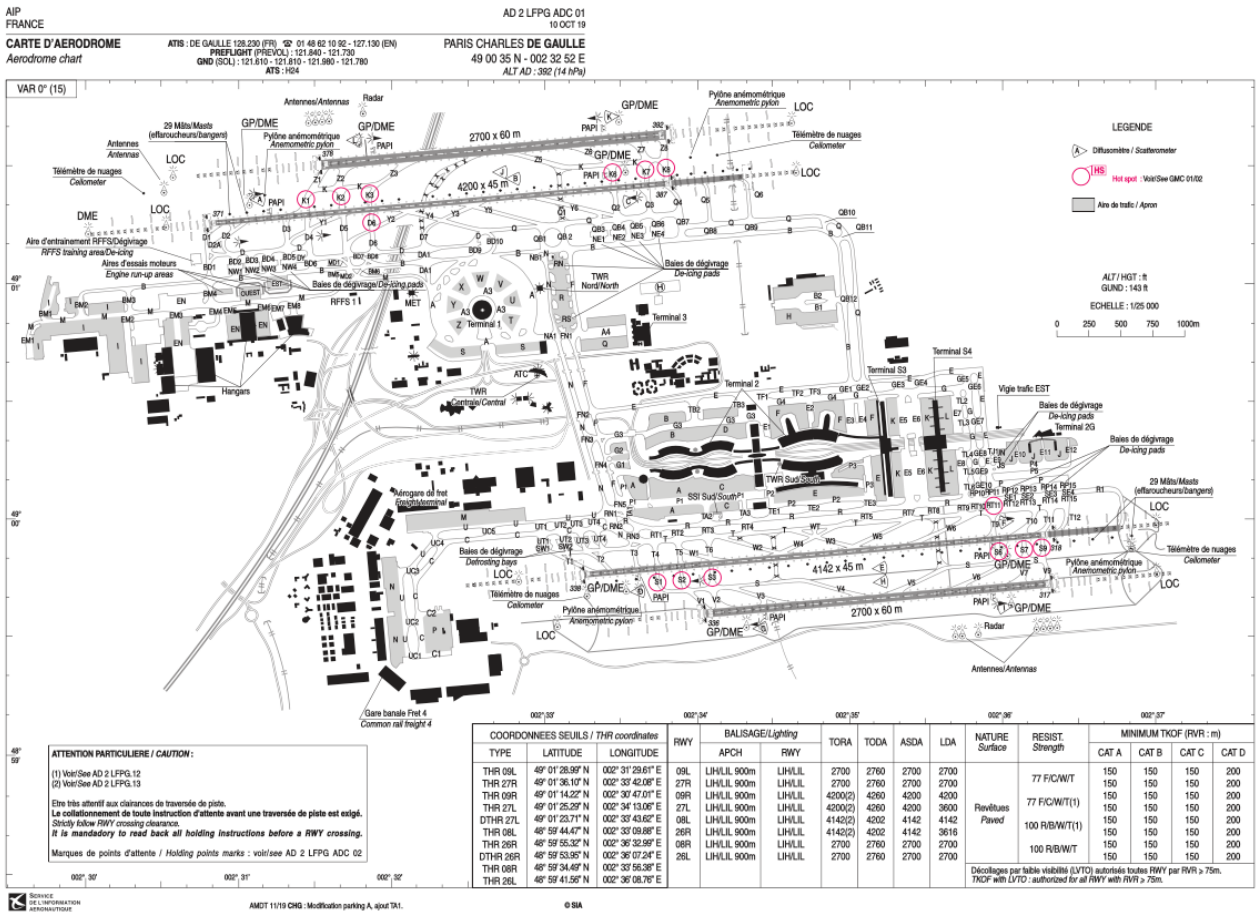


*Figure 2 CDG Airport Model Representation. Overview of the actual infrastructure, runways, and terminals.*

### Network Representation

Different components of airport are considered using a network abstraction (see Figure 3). Runways, terminals, gates, and ground handling teams are modelled as resources with a specific capacity corresponding to Paris Charles de Gaulle (CDG) Airport. We consider the overall capacity of a terminal also considering its individual gates availability. Taxiway is seen as a node with a threshold of total allowed number of taxi-in and taxi-out aircraft related to the aircraft incoming/ongoing to the apron. The gates are assigned depending on the terminal and wake turbulence category. The ground handling teams are also assigned depending on the terminal, gate, service according to the wake turbulence category.

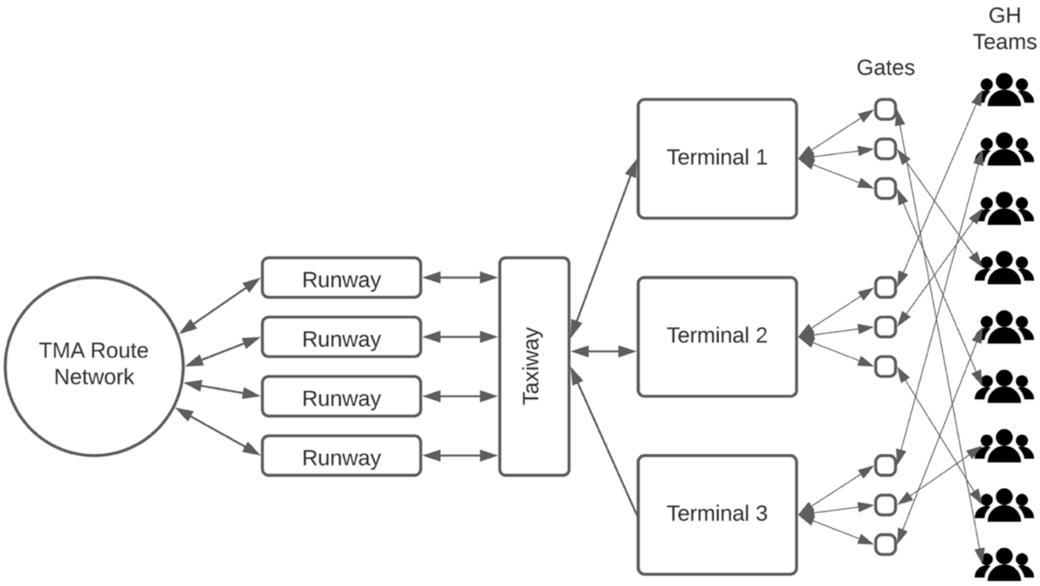


*Figure 3 Network representation*

**Mathematical Formulation**

The following notations are defined for our problem formulation:

- $\mathcal{F}$: set of flights, $\mathcal{F} = \mathcal{A} \cup \mathcal{D}$;
- $\mathcal{A}$: set of arrivals;
- $\mathcal{D}$: set of departures;
- $\mathcal{AD}$: set of arrival-departures;
- $\mathcal{R}$: set of landing or take-off runways;
- $I_f$: initial off-block time for departure or landing time for arrival. Note that the landing time of each arrival is predetermined and is not optimized in this study;
- $C_{f,g}$: Maximum capacity in terms of flow.
- $\mathcal{T}$: set of terminals;
- $\mathcal{G}_{\mathcal{T}}$: set of gates for terminals $T$;
- $\mathcal{GH}$: set of ground handling teams for each flight;
- $N^a$: maximum allowed number of holding time slots for arrivals;
- $N^d$: maximum allowed number of holding time slots for departures;
- $N_p$: maximum allowed number of pushback delay time slots;
- $\Delta t$: time step;
- $\Delta v$: speed increment;

- $\mathcal{S}_{\mathrm{f,g}}$: minimum separation between these two aircraft;
- $d_{fg}^{u}$(x): actual separation distance of these aircraft at the entry time;
- $d_{fg}^{v}$(x): actual separation distance of these aircraft at the exit time.

We are given a set of flights (or aircraft), $\mathcal{F} = \mathcal{A} \cup \mathcal{AD} \cup \mathcal{D}$, where $\mathcal{A}$ is the set of arrivals (flights that arrive at the airport and stay until the end of the day), $\mathcal{AD}$ is the set of arrival-departures (flights that arrive at the airport and depart from it after a turnaround duration), $\mathcal{D}$ is the set of departures (flights that are parked at the airport at the beginning of the day and depart later). For each flight $f \in \mathcal{F}$, the following data is given: wake turbulence category for $f \in \mathcal{F}$, assigned terminal for $f \in \mathcal{F}$, entering waypoint at TMA for $f \in \mathcal{A} \cup \mathcal{AD}$, exit waypoint at TMA for $f \in \mathcal{D} \cup \mathcal{AD}$, taxi-in duration for $f \in \mathcal{A} \cup \mathcal{AD}$, taxi-out duration for $f \in \mathcal{D} \cup \mathcal{AD}$, initial landing runway number for $f \in \mathcal{A} \cup \mathcal{AD}$ (usually the requested landing runway is linked to the relative position of the terminal and the landing runways), initial departure runway number for $f \in \mathcal{D} \cup \mathcal{AD}$, initial off-block time for $f \in \mathcal{D}$, turnaround duration for $f \in \mathcal{AD}$ and initial exit time at the exit SID waypoint for $f \in \mathcal{D} \cup \mathcal{AD}$.

Moreover, we know:

- $T_f^0$: initial RTA (Required Time of Arrival) at the entering waypoint of TMA ($f \in \mathcal{A} \cup \mathcal{AD}$);
- $V_f^0$: initial speed at the entering waypoint of TMA ($f \in \mathcal{A} \cup \mathcal{AD}$);
- $P_f^0$: initial off-block time ($f \in \mathcal{D} \cup \mathcal{AD}$), it is the earliest time that an aircraft is ready to depart from its parking position.

Here are the assumptions and simplifications we make for our model:

- Flights are assigned to gates in their terminal;
- We use an average taxi-in and taxi-out duration regarding terminal and runway for each flight. Detailed study of airport taxi routings can be found in [Ma, Delahaye, Sbihi, Scala and Mota (2017a)]
- Each aircraft has a constant deceleration or acceleration in the TMA.
- The ground handling teams are assigned to the flights.

**Decision Variables**

The optimization model we are using has eight types of decision variables. For arrivals, we have to attribute the entering time in the TMA, the entering speed in the TMA, the landing runway, the gate and the ground handling team for arrival:

1. Entering time in the TMA for $f \in \mathcal{A} \cup \mathcal{AD}$: First, we assume that we are given a maximum delay and a maximum advance, denoted respectively $\Delta T_{max}$ and $\Delta T_{min}$, which define the range of possible entering times in the TMA. We therefore define, for each flight $f \in \mathcal{A} \cup \mathcal{AD}$, a time-slot decision variable $t_f \in \mathcal{T}_f$, where

   $\mathcal{T}_f = \{T_f^0 + j\Delta T \mid \frac{\Delta T_{min}}{\Delta T} \leq j \leq \frac{\Delta T_{max}}{\Delta T}, j \in \mathbb{Z}\}$,

   where $\Delta T$ is a discretized time increment, whose value is to be set by the user. In order to shift an aircraft entering time in the TMA, we can either decrease or increase its speed in the en-route phase. In practice, the latter strategy burns more fuel, and may be far less attractive for the airlines. Therefore, our time slot interval can be asymmetric, with $|\Delta T_{max}| \geq |\Delta T_{min}|$. In the following sections, the notation *delay* is used to indicate the time deviation of a flight.

2. Entering speed in the TMA for $f \in \mathcal{A} \cup \mathcal{AD}$: $v_f \in \mathcal{V}_f$, where

   $\mathcal{V}_f = \{V_f^{min} + j\Delta_f^v \mid j \in \mathbb{Z}, |j| \leq (V_f^{max} - V_f^{min}/\Delta_f^v)\}$,

   with $\Delta_f^v$ is a (user-defined) speed increment, $V_f^{min}$ and $V_f^{max}$ are given as input data corresponding to the minimum and maximum allowable speeds for aircraft $f$.

3. Landing runway for $f \in \mathcal{A} \cup \mathcal{AD}$: $r_f^l$ is the landing runway decision for arrivals. Runway assignment is used to balance the capacity when one runway gets overloaded while another one is still able to accommodate more aircraft.

4. Gate for $f \in \mathcal{A} \cup \mathcal{AD}$: $G$ is the decision of which gate assigned to the flight $f$ according to its terminal.

5. Arrival Ground handling Team for $f \in \mathcal{A} \cup \mathcal{AD}$: $GH_A$ is the decision variable of which ground handling team for arrival will serve the flight $f$. For departures, we have to decide the ground handling, departure runway and the pushback time.

6. Departure Ground handling Team for $f \in \mathcal{A} \cup \mathcal{AD}$: $GH_D$ is the decision variable of which ground handling team for departure will serve the flight $f$.

7. Departure runway for $f \in \mathcal{D} \cup \mathcal{AD}$: $r_f^d$ is the take-off runway decision variable for departures. Similarly, it is possible to yield flights to another take-off runway when the current assigned one is too busy.

8. Pushback time for $f \in \mathcal{D} \cup \mathcal{AD}$: $p_f \in \mathcal{P}_f$, where

   $\mathcal{P}_f = \{P_f^0 + j\Delta T | 0 \leq j \leq \frac{\Delta T_{max}^p}{\Delta T}, j \in \mathbb{N}\}$,

   where $\Delta T_{max}^p$ is the maximum pushback delay. In contrast to the entering time decision in the TMA for arrival flights, we can only delay a departure with regard to its earliest initial off-block time. Pushback time for departures is discretized into time slots, $p_f \in \{I_f, I_f + \Delta t, I_f + 2.\Delta t, \ldots, I_f + N_p.\Delta t\}$.

To summarize, our decision vector is $\mathbf{x} = (\mathbf{t}, \mathbf{v}, \mathbf{l}, \mathbf{g}, \mathbf{d}, \mathbf{p}, \boldsymbol{GH_a}, \boldsymbol{GH_d})$, where $\mathbf{t}$ is the entering time vector, $\mathbf{v}$ is the entering speed vector, $\mathbf{l}$ is the landing runway vector, $\mathbf{g}$ is for the gate assignment vector, $\mathbf{d}$ is the departure runway vector, $\mathbf{p}$ is the pushback time vector, $\boldsymbol{GH_a}$ is the ground handling team assigned for arrival flights and $\boldsymbol{GH_d}$ is the ground handling team assigned for departure flights.

**Constraints**

We have three main constraints: wake turbulence separation, single-runway separation for arrivals and departures, and maximum pushback delay.

For two consecutive flights *f*, *g* that are flying through a link *l* = (*u*,*v*), the minimum separation between these two aircraft, $\mathcal{S}_{f,g}$ , is obtained based on their respective wake turbulence category as shown in Table 1, the separation minima regulations are given by ICAO [ICAO, 2016]. Then, the actual separation distance of these aircraft at the entry time, $d_{fg}^u(\mathrm{x})$, and at the exit time of link *l*, $d_{fg}^v(\mathrm{x})$ are computed and compared with $\mathcal{S}_{f,g}$ to detect potential link conflict.

*Table 1 Distance-based separation on approach and departure according to aircraft categories (in NM).*

| Category | | Trailing Aircraft | | |
|---|---|---|---|---|
| | | **Heavy** | **Medium** | **Light** |
| Leading Aircraft | **Heavy** | 4 | 5 | 6 |
| | **Medium** | 3 | 3 | 5 |
| | **Light** | 3 | 3 | 3 |

The landing/take-off time difference of any two consecutive aircraft must respect the time separation. The runway separation rules are calculated by incorporating the different flight speeds and their impact on the final approach segment. The separation requirements are shown in Table 2, where A refers to Arrival, D refers to Departure, and C refers to Crossing. Due to the runway configuration in CDG, arrivals have to cross departure runways to get to the terminal. We consider that the crossing time of an arrival is 40 seconds.

One runway can be modeled as a specific resource with capacity 1. During high traffic demand periods, the upcoming flights may violate the separation rules and cause runway congestions.

*Table 2 Single-runway separation requirements according to aircraft categories and to operations (in seconds).*

| Operation-Category | | Trailing Aircraft | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **A-H** | **A-M** | **A-L** | **D-H** | **D-M** | **D-L** | **C** |
| Leading Aircraft | **A-H** | 96 | 157 | 207 | 60 | 60 | 60 | - |
| | **A-M** | 60 | 69 | 123 | 60 | 60 | 60 | - |
| | **A-L** | 60 | 69 | 82 | 60 | 60 | 60 | - |
| | **D-H** | 60 | 60 | 60 | 96 | 120 | 120 | 60 |
| | **D-M** | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| | **D-L** | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| | **C** | - | - | - | 40 | 40 | 40 | 10 |

The decision variables of each flight must satisfy the following constraints: the maximum pushback delay.

$$I_f \leq P_f \leq I_f + N_p.\Delta t, \quad \forall f \in D$$

**Objective function**

Our objective function is a weighted sum of the overloads for gates, terminal, ground handling teams and for taxi network and flight delays.

- Terminal and taxiway congestion evaluation:

  We have two metrics to measure the terminal congestion. First, the maximum overload number is the maximum value over the period of the difference between the number of aircraft in the terminal and the given terminal capacity. This metric gives us an idea of the time at which severe congestion occurs. However, the maximal overload does not provide sufficient information on the level of congestion. Therefore, another important metric to consider is the average congestion.

Suppose that we have a discretized time window $\mathcal{T} = \{1,2,\ldots,|\mathcal{T}|\}$, let us define the *occupancy indicator* for $t_i \in \mathcal{T}$:

$O_m(t_i) = \text{Card}\{f|T_{In}^{f,m}(\mathbf{x}) \leq t_i \leq T_{Out}^{f,m}(\mathbf{x})\}$

where $T_{In}^{f,m}(\mathbf{x})$ and $T_{Out}^{f,m}(\mathbf{x})$ correspond to the entering time and the exit time of resource $m$ (i.e., terminal or taxi network). It counts the number of aircraft at time $t_i$. The overload of resource $m$ at time $t_i$ is then defined as:

$G_m(t_i) = \max\{O_m(t_i) - O_m, 0\}$

where $O_m$ is the imposed maximum capacity of the resource $m$.

The average overload is then defined as $\frac{\sum_{t_i \in \mathcal{T}} G_m(t_i)}{|\mathcal{T}|}$.

To conclude, the airside capacity overload is expressed as

$$S(\text{x}) = \frac{\sum_{t_i \in \mathcal{T}} G_t(t_i)}{|\mathcal{T}|} + \max_{t_i \in \mathcal{T}} G_t(t_i) + \frac{\sum_{t_i \in \mathcal{T}} G_n(t_i)}{|\mathcal{T}|} + \max_{t_i \in \mathcal{T}} G_n(t_i)$$

where $G_t(t_i)$ and $G_n(t_i)$ are respectively the terminal overload and the taxi network overload at time $t_i$.

- Flight delays: The flight delays $D(\text{x})$ are defined as the total time deviation between the optimized and initial values of RTA and pushback time, $D(\text{x}) = \sum_{f \in \mathcal{F}}(p_f - P_f^0) + \sum_{f \in \mathcal{F}}(t_f - T_f^0)$.

The optimization model aims at minimizing the objective function, depending on which component the optimization process should focus on, these weights can be adjusted accordingly. Thus, our objective function, to be minimized is therefore a weighted sum of these functions:

$$\gamma_a A(\mathbf{x}) + \gamma_s S(\mathbf{x}) + \gamma_d D(\mathbf{x}) + \gamma_g G(\mathbf{x}) + \gamma_h GH(\mathbf{x}) + \gamma_l S_p(\mathbf{x})$$

where $\gamma_a, \gamma_s, \gamma_d, \gamma_g, \gamma_h$ and $\gamma_l$ are respectively weighting coefficients for the total number of conflicts in airspace, $A(\mathbf{x})$, the airside capacity overload, $S(\mathbf{x})$, the flight delays $D(\mathbf{x})$, the gate capacity overload $G(\mathbf{x})$, the ground handling performance $GH(\mathbf{x})$ and $S_p(\mathbf{x})$ the speed deviation.

**Simulated Annealing**

Simulated Annealing (SA) is one of the best-known metaheuristic methods for addressing the difficult *black box* global optimization problems (those whose objective function is not explicitly given and can only be evaluated via some costly computer simulation).

Simulated annealing has been applied to many highly combinatorial problems coming from industry and operations; to mention a few:

- Airline crew scheduling
- Railway crew scheduling
- Traveling salesman problem
- Vehicle routing problem
- Layout-routing of electronic circuits
- Large scale aircraft trajectory planning

- Complex portfolio problem
- Graph colouring problem
- High-dimensionality minimization problems

These concepts are based on a strong analogy with the physical annealing of materials. This process involves bringing a solid to a low energy state after raising its temperature. It can be summarized by the following two steps:

- Bring the solid to a very high temperature until "melting" of the structure;

- Cooling the solid according to a very particular temperature decreasing scheme to reach a solid state of minimum energy.

In the liquid phase, the particles are distributed randomly. It is shown that the minimum-energy state is reached provided that the initial temperature is sufficiently high, and the cooling time is sufficiently long. If this is not the case, the solid will be found in a metastable state with non-minimal energy; this is referred to as *hardening*, which consists in the sudden cooling of a solid.

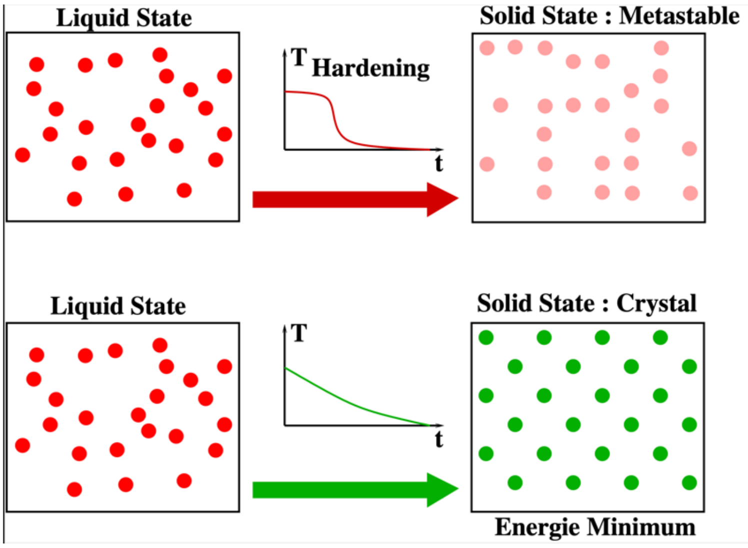


*Figure 4 When temperature is high, the material is in a liquid state (left). For a hardening process, the material reaches a solid state with non-minimal energy (metastable state; top right). In this case, the structure of the atoms has no symmetry. During a slow annealing process, the material also reaches a solid state but for which atoms are organized with symmetry (crystal; bottom right).*

In the next definitions we consider $(S, f)$ an instantiation of a combinatorial optimization problem ($S$: space of feasible solutions, $f$: optimization function to be minimized).

Definition 1. Let $\mathcal{N}$ be an application that defines for each solution $i \in S$ a subset $S_i \subset S$ of solutions "close" (to be defined by the user according to the problem of interest) to the solution $i$. The subset $S_i$ is called the *neighbourhood* of solution $i$.

In the next definitions, we consider that $\mathcal{N}$ is a neighborhood structure associated to $(S, f)$.

Definition 2. A *generating mechanism* is a mean for selecting a solution $j$ in any neighborhood $S_i$ of a given solution $i$.

Definition 3. Let $(S, f)$ be an instantiation of a combinatorial minimization problem, and $i, j$ two points of the state space. The *acceptance criterion* for accepting solution $j$ from the current solution $i$ is given by the following probability:

$$Pr\{\text{ accept } j\} = \begin{cases} 1 & \text{if } f(j) < f(i) \\ \exp\left(\dfrac{f(i) - f(j)}{c}\right) & \text{else.} \end{cases}$$

Then, the neighborhood generation principle is similar to the perturbation mechanism of the Metropolis algorithm, and the acceptance criterion represents the Metropolis principle. A *transition* is defined as the replacement of the current solution by a neighboring solution, it consists of the neighborhood generation and acceptance. In the sequel, let $c_k$ be the value of the temperature parameter, and $L_k$ be the number of transitions generated at some iteration $k$. The principle of SA can be summarized as follows:

**Simulated annealing**

1. Initialization $i := i_{start}$, $k := 0$, $c_k = c_0$, $L_k := L_0$);
2. Repeat
3. For $l = 0$ to $L_k$ do
   - Generate a solution $j$ from the neighborhood $S_i$ of the current solution $i$;
   - If $f(j) < f(i)$ then $i := j$ ($j$ becomes the current solution);
   - Else, $j$ becomes the current solution with probability $e^{\left(\frac{f(i)-f(j)}{c_k}\right)}$;
4. $k := k + 1$;
5. Compute $(L_k, c_k)$;
6. Until $c_k \simeq 0$

One of the main features of simulated annealing is its ability to accept transitions that degrade the objective function.

At the beginning of the process, the value of the temperature $c_k$ is high, which makes it possible to accept transitions with high criterion degradation, and thereby to explore the state space thoroughly. As $c_k$ decreases, only the transitions improving the criterion, or with a low criterion deterioration, are accepted. Finally, when $c_k$ tends to zero, no deterioration of the criterion is accepted, and the SA algorithm behaves like a Monte Carlo algorithm.

**Sliding Window Approach**

The sliding window approach consists in considering time frame windows of small size and shifting them along the entire time horizon of the study. By using this approach, a small instance of the problem is solved considering only the elements within the time window (see Figure 5) illustrates the approach. The main parameters to set are the window length and the shift length. The main advantages coming from the use of this method are less computational time required; the possibility of treating the problem in a dynamic way, by considering, as time passes, new information updates due to changes in the environment and to the interactions between entities with the surrounding environment.

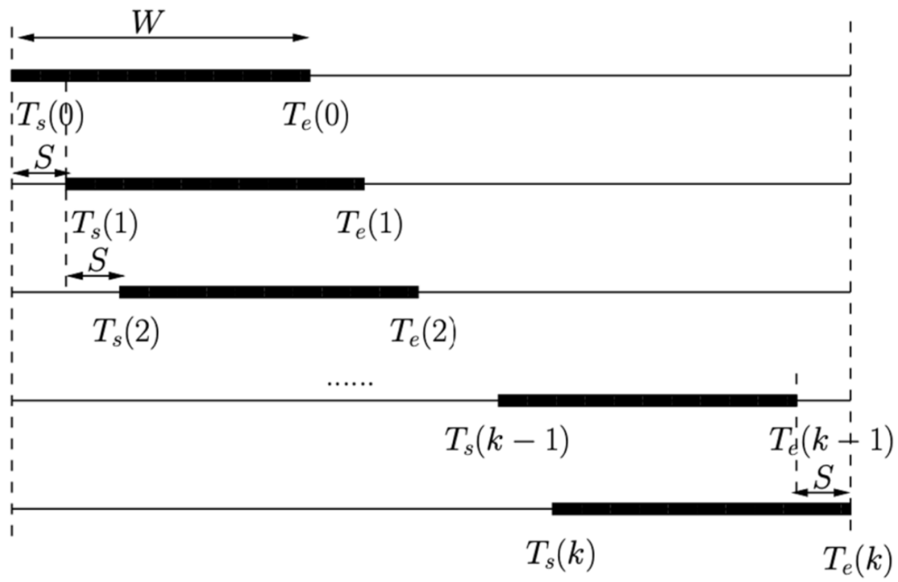


*Figure 5 Sliding Window from iteration 0 to iteration k with the time length w and the time shift s for each iteration.*

Suppose that we are given a total time interval, $[t_{INIT}, t_{FINAL}]$, over which we want to optimize. Let us introduce some notations:

- $W$: the time length of the sliding window;
- $S$: the time shift of the sliding window at each iteration;
- $T_s(k)$: the starting time of the $k^{th}$ sliding window, $T_s(k) = t_{INIT} + kS$;
- $T_e(k)$: the ending time of the $k^{th}$ sliding window, $T_e(k) = t_{INIT} + kS + W$.

Figure 5 illustrates how the operating window slides along the time axis. The first sliding window begins at $t_{INIT}$ and, the optimization algorithm (to be defined later) is applied in the corresponding time interval $[T_s(0), T_e(0)]$. Next, the sliding window is shifted by time $S$, and the current optimizing interval becomes $[T_s(1), T_e(1)]$. Then, we repeat the process until we reach the $k^{th}$ sliding window such that $T_e(k) =\leq t_{FINAL} - S$.

Some parameters are needed to describe the sliding-window approach for each flight $f \in \mathcal{F}$:

- $t_s^f$: the initial starting time, i.e.,

$$t_s^f = \begin{cases} T_f^0 \text{ if } f \in A \cup AD \\ P_f^0 \text{ if } f \in D \end{cases}$$

- $\underline{t_s^f}$: the earliest starting time, i.e.,

$$\underline{t_s^f} := \begin{cases} t_s^f + \Delta T_{min} & \text{if } f \in A \cup AD \\ t_s^f & \text{if } f \in D \end{cases}$$

- $\overline{t_s^f}$: the latest starting time, i.e.,

$$\overline{t_s^f} := \begin{cases} t_s^f + \Delta T_{min} \text{ if } f \in A \cup AD \\ t_s^f + \Delta T_{max}^p \text{ if } f \in D \end{cases}$$

- $t_e^f$: the initial ending time, i.e.,
    - For $f \in \mathcal{A}$, it corresponds to the initial in-block time, which is computed with regard to the initial entry time, the STAR route, the initial entry speed, and the average taxi-in duration;
    - For $f \in \mathcal{AD}$, it is the exit time of TMA, computed with regard to the initial entry time, the STAR route, the initial entry speed, the average taxi-in duration, the turnaround duration, the average taxi-out duration, the take-off time, and the SID route;
    - For $f \in \mathcal{D}$, it is also the exit time of TMA, computed regard to the earliest off-block time, the average taxi-out duration, the take-off time, and the SID route.
- $\underline{t_e^f}$: the earliest ending time, i.e.,
    - For $f \in \mathcal{A}$, it corresponds to the earliest in-block time, which is computed with regard to the earliest entry time in the TMA, the maximum entry speed, STAR route, and the average taxi-in duration;
    - For $f \in \mathcal{AD}$, it is the earliest exit time of TMA, computed with regard to the STAR route, earliest entry time in the TMA, the maximum entry speed, the average taxi-in duration, the turnaround time, the earliest pushback time, the average taxi-out duration, the take-off time, and the SID route;
    - For $f \in \mathcal{D}$, it is also the earliest exit time of TMA, computed regarding the earliest off-block time, the average taxi-out duration, the take-off time, and the SID route.
- $\overline{t_e^f}$: the latest ending time, i.e.,
    - For $f \in \mathcal{A}$, it corresponds to the latest in-block time, which is computed with regard to the latest entry time in the TMA, the minimum entry speed, the STAR route, and the average taxi-in duration;
    - For $f \in \mathcal{AD}$, it is the latest exit time of TMA, computed with regard to the STAR route, the latest entry time in the TMA, the minimum entry speed, the average taxi-in duration, the turnaround time, the latest pushback time, the average taxi-out duration, the take-off time, and the SID route;
    - For $f \in \mathcal{D}$, it is also the latest exit time of TMA, computed regarding the latest off-block time, the average taxi-out duration, the take-off time, and the SID route.

Each aircraft is classified into four different statuses: **completed**, **on-going**, **active,** and **planned**, based on its operation time interval relative to the sliding window (see Figure 6). Completed means that the aircraft has already finished its operations before the start of the current sliding window. On-going means that a part of the flight trajectory is still in the sliding window but the decisions for this aircraft are already taken, therefore it may impact the assignment of the following aircraft. We can change the decision variables of active aircraft to optimize the operations. Planned flights will be considered in the next sliding windows. At each step, we consider the active and on-going aircraft in the sliding window interval to be optimized. Then, the optimization window recedes in the future by a fixed time step. The status of aircraft is updated, a new set of flights waiting to be addressed are considered, and the optimization process is repeated.

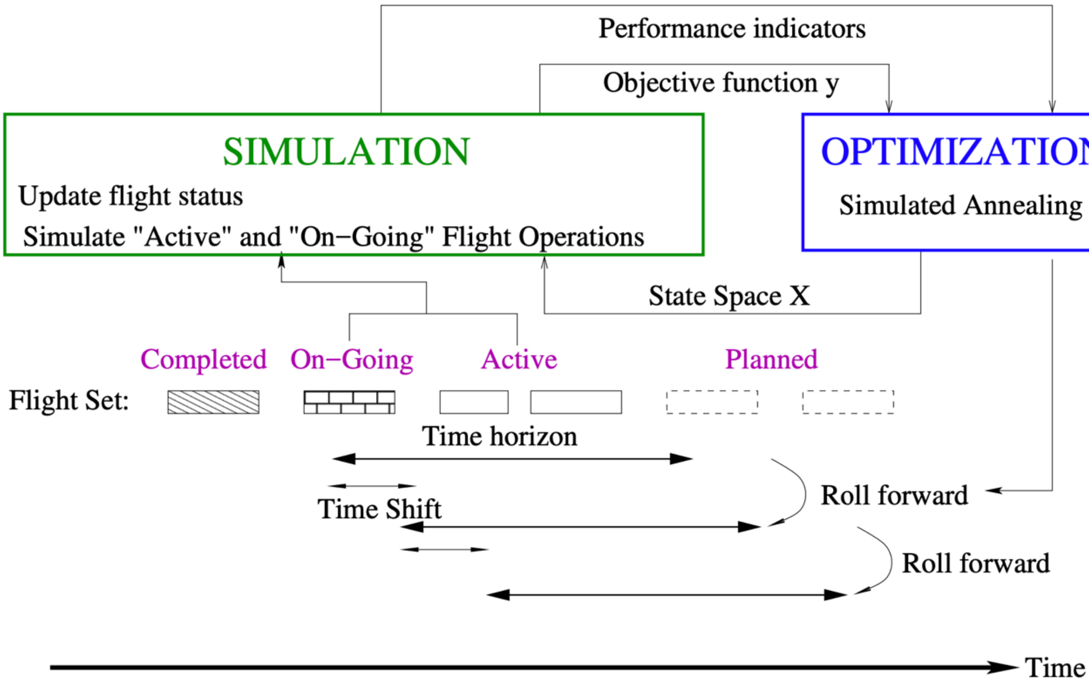


*Figure 6 Sliding Window. The sliding window approach with the different flight status and the process of optimization-simulation.*

## 6. Description of the data the study relies on

The data used was one day of operations from Paris Charles de Gaulle, the data was from 18 February 2016, with a total of 726 flights. The different input data are listed below in the next tables. Table 3 contains the information of the average taxi-out time duration according to the terminal and the runway. Table 4 contains the information of the average taxi-in time duration according to the terminal and the runway. Table 5 contains the information of the average service time according to the wake turbulence category and to the operations. Table 6 describes the number of gates according to the terminal.

*Table 3 Average Taxi-out Time Duration according to terminal and runway (seconds).*

| Take-off Runway | Terminal 1 (sec) | Terminal 2 (sec) | Terminal 3 (sec) |
|---|---|---|---|
| **27L** | 720 | 890 | 880 |
| **26R** | 1400 | 760 | 710 |

*Table 4 Average Taxi-in Time Duration according to terminal and runway (seconds).*

| Landing Runway | Terminal 1 (sec) | Terminal 2 (sec) | Terminal 3 (sec) |
|---|---|---|---|
| **27R** | 400 | 730 | 680 |
| **26L** | 535 | 500 | 530 |

*Table 5 Average service time according to aircraft categories and to operations (minutes).*

| Wake Turbulence Category (WtCat) | Arrival Service Time (min) | Departure Service Time (min) |
|---|---|---|
| **Light** | 20 | 30 |
| **Medium** | 30 | 40 |
| **Heavy** | 40 | 60 |

*Table 6 Number of gates according to terminal.*

| Terminal | Gates |
|---|---|
| **Terminal 1** | 20 |
| **Terminal 2** | 125 |
| **Terminal 3** | 46 |
| **Total** | 191 |

# 7. Computational experiments

We have defined the mathematical model with the variables, constraints, and the associated objective function, we also defined the simulated annealing principles. This section describes the adaptation of SA to the problem of integrated air traffic optimization in airports and TMA and the application to our problem will be introduced.

For each time window, the simulation process takes the decision proposed by the optimization algorithm and simulates the associated flights to produce the associated objective function (see Figure 7). Each flight is simulated in the airspace by using the decisions proposed by the simulated annealing. The flight may encounter conflicts in the airspace or at runways with other aircraft; it may also be involved in some terminal or taxi congestion. It may also have default in Ground Handling service or be in conflict at the gate with some other aircraft. All those events are registered on the flight to establish the performance of its decision vector. Based on such performance computation, the flights with the lowest performances are statistically selected to undergo the neighbourhood operator of the simulated annealing to change the associated decisions.

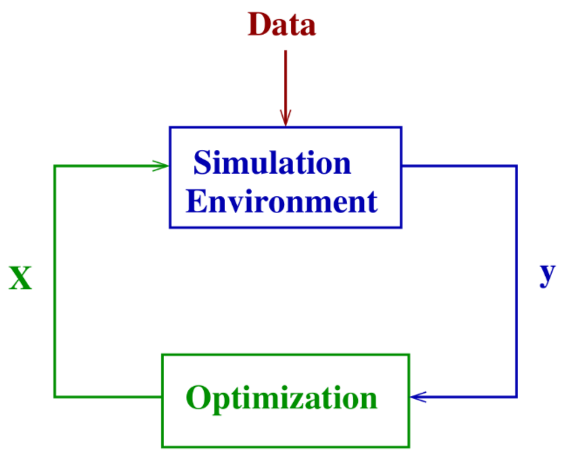


*Figure 7 Objective-function evaluation based on a simulation process.*

Figure 8 represents the different phases of the simulation optimization process for the turnaround. When the aircraft first approach to the TMA STAR for the arrival process. It is assigned an RTA, an arrival speed (in the TMA) and landing runway. Then, depending on the terminal and the wake turbulence category a gate is assigned to the aircraft with ground handling team for arrival process followed by the ground handling team for departure, a push back delay and finally the take-off runway.

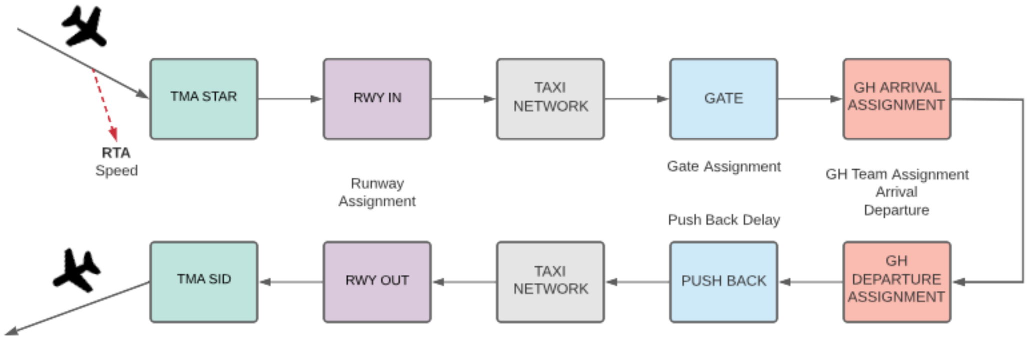


*Figure 8 Simulation Optimization Process for each phase. It shows the decision taken on each phase of the turnaround.*

Figure 6 summarizes the overall optimization process. The parameters chosen for specifying the resolution algorithm are given in Table 7. The simulation process takes the decision proposed by the optimization algorithm and simulates the associated flights in order to produce the objective function and the vector of performances. The objective function and the performance indicators provided by the simulation process guide the optimization module to search for better solution. The time sliding window manager updates flight statuses and puts them into the two previous mentioned modules. The optimization and simulation processes are repeated.

We apply the simulated annealing algorithm combined with time decomposition approach to resolve the integrated terminal airspace management problem and airport capacity management problem.

The solution was implemented on a 2.3 GHz Dual-Core Intel Core i5, under Mac OS X operating system based on Java code. The maximum computation time for 30 min intervals is 4 minutes for CDG.

*Table 7 User-defined parameter values specifying the optimization problem and parameter values of the simulated annealing algorithm.*

| Parameters | Value |
|---|---|
| Discretization time step $\boldsymbol{\Delta t}$ | 5 seconds |
| Discretization speed step $\Delta_{\boldsymbol{f}}^{\boldsymbol{v}}$ | 0.01 $V_f^0$ |
| Maximum delay of RTA at TMA $\Delta\boldsymbol{T}_{\boldsymbol{max}}$ | 30 minutes |
| Minimum delay of RTA at TMA $\Delta\boldsymbol{T}_{\boldsymbol{min}}$ | -5 minutes |
| Maximum pushback delay $\Delta\boldsymbol{T}_{\boldsymbol{max}}^{\boldsymbol{p}}$ | 15 minutes |
| Minimum allow speed $\boldsymbol{V}_{\boldsymbol{f}}^{\boldsymbol{min}}$ | 0.9 $V_f^0$ |
| Maximum allow speed $\boldsymbol{V}_{\boldsymbol{f}}^{\boldsymbol{max}}$ | 1.1 $V_f^0$ |
| Conflicts weight coefficient $\boldsymbol{\gamma_a}$ | 1 |
| Overload weight coefficient $\boldsymbol{\gamma_s}$ | 1 |
| Delay weight coefficient $\boldsymbol{\gamma_d}$ | 0.001 |
| Geometrical temperature reduction coefficient | 0.99 |
| Number of iterations at each temperature step | 100 |
| Initial rate of accepting degrading solutions | 0.15 |
| Final temperature | $10^{-6}$ $T_0$ |
| Time length of the sliding window | 2 hours |
| Time shift of the sliding window | 0.5 hours |

## 8. Results

The data used was one day of operations from Paris Charles de Gaulle, the data was from 18 February 2016, with a total of 726 flights, where 506 were Arrival-Departure, 114 Arrivals and 106 Departures. From which 1 was a Light aircraft, 558 Medium and 167 Heavy, so, the fleet mix ratio on this day is Light=0.14 %, Medium=76.86 % and Heavy=23 %. Regarding the usage of the Terminals and Gates (Table 4), it is important to highlight that Terminal 1 consists of a central circular terminal building and seven satellites with boarding gates, thus cannot handle many aircraft and keeps a stable low traffic over the day. Air France operates from Terminal 2, and Paris Charles de Gaulle (CDG) is the principal hub for Air France (hub airport is used by one airline to concentrate passenger traffic and flight operations at a given airport), so, Terminal 2 is the main terminal of CDG that serves most aircraft. Therefore, we observed much more traffic flows in Terminal 2 compared to the other two terminals. Terminal 3 mainly hosts charter and low-cost airlines, is mainly composed of hangars for night parking, therefore the departure flights leave the terminal early in the morning and the arrival flights come late at night, therefore the departure flights leave the terminal early in the morning and the arrival flights come late at night. So, the result from the optimization gave us that the Terminal 1 had a total of 105 flights, Terminal 2 had 522 and Terminal 3 had 99, during one day of operations.

Tables 3 and 4 show that there are four parallel runways that two are used mostly for the departures (26R, 27L) and the other two for arrivals (26L, 27R). Table 8 shows the results of the usage of the number of aircrafts per runway.

*Table 8 Results for runways usage.*

| Runway | Runway in | Runway out |
|---|---|---|
| **27R** | 114 | 106 |
| **26L** | 217 | 0 |
| **26R** | 395 | 286 |
| **27L** | 0 | 336 |

Figure 9 and Figure 10 shows the initial sequency related to the runway's saturation and the number of flights for each runway and we made the comparison with the optimization done. Figure 9 is related to the take-off runways (26R and 27L) and Figure 10 is related to the landing runways (27R and 26L).

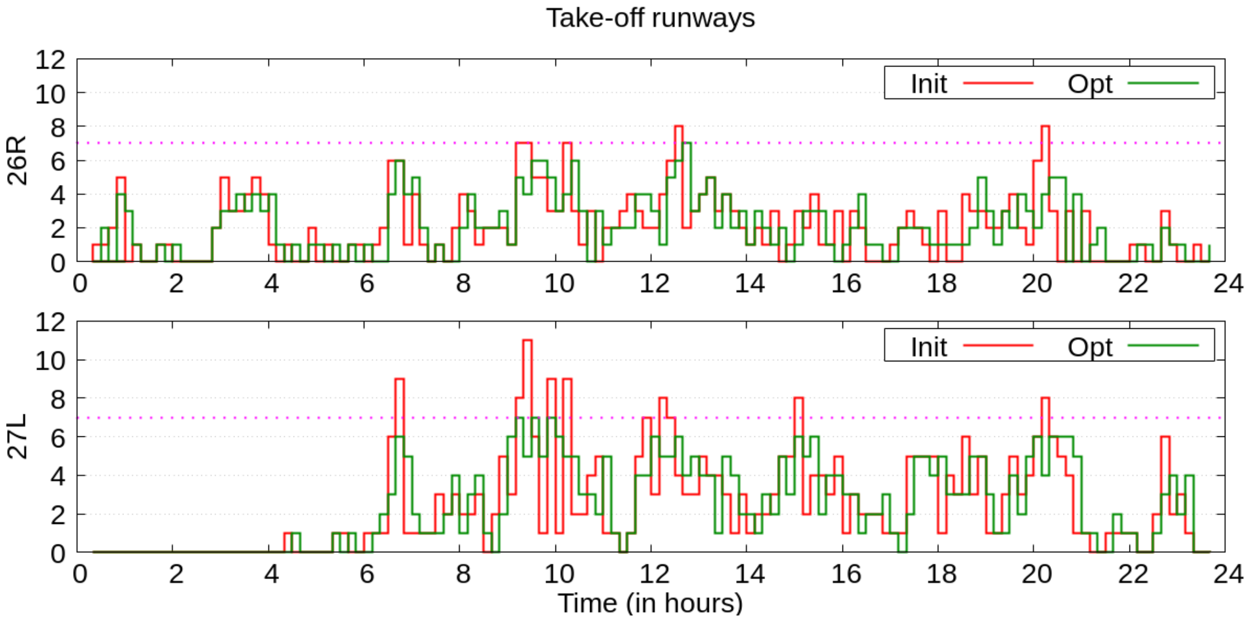


*Figure 9 Comparison between the initial take off runway sequency and the sequency after the optimization.*

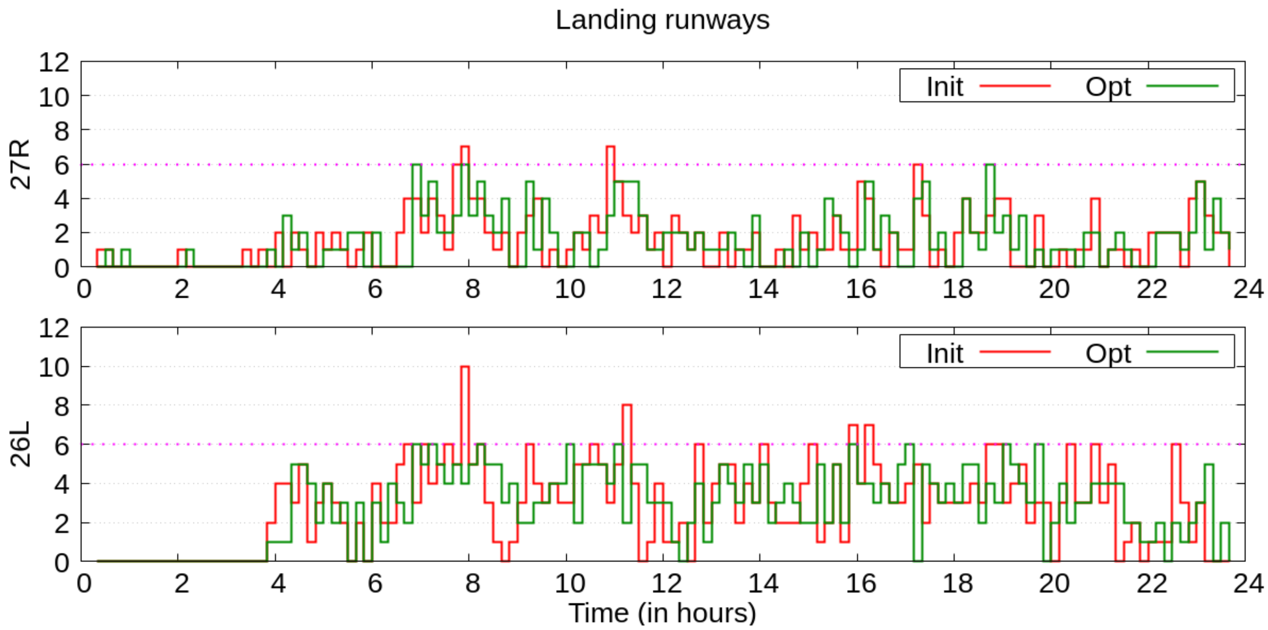


*Figure 10 Comparison between the initial landing runway sequency and the sequency after the optimization.*

The next Figure 11 shows the number of flights depending on the terminals, as we said before the terminal 2 is the one with the highest demand, the highest number of flights is between 8 am and 10 am, the terminal 1 and terminal 3 do not have a lot of flights per hour.

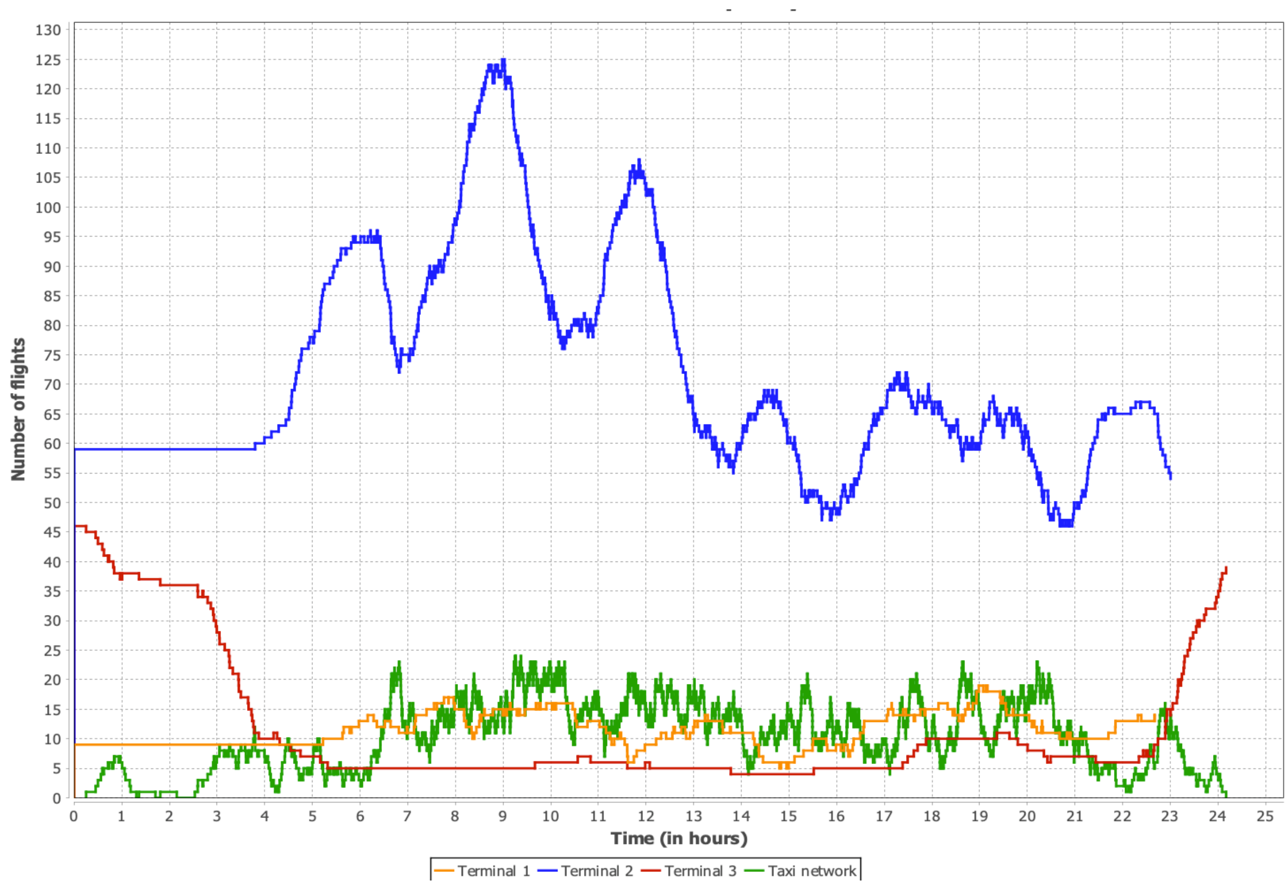


*Figure 11 Number of flights per hour including the taxi network occupancy.*

# 9. Analysis of the results

The evaluation of the performance of the different components of the optimization are shown in the next figures. The main key performance indicators for this study are the ones related to the evaluation of the runways (Figure 11), terminals (Figure 13), gates (Figure 14) and ground handling teams (Figure 15).

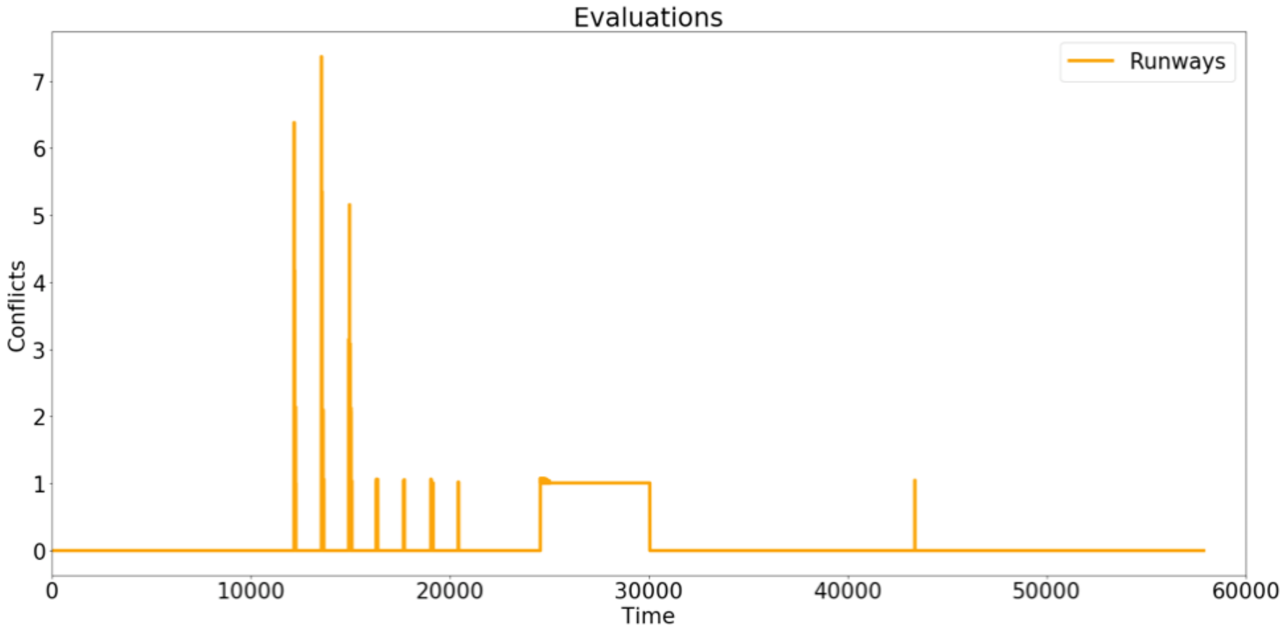


*Figure 12 Evaluation runway conflicts for the operation day.*

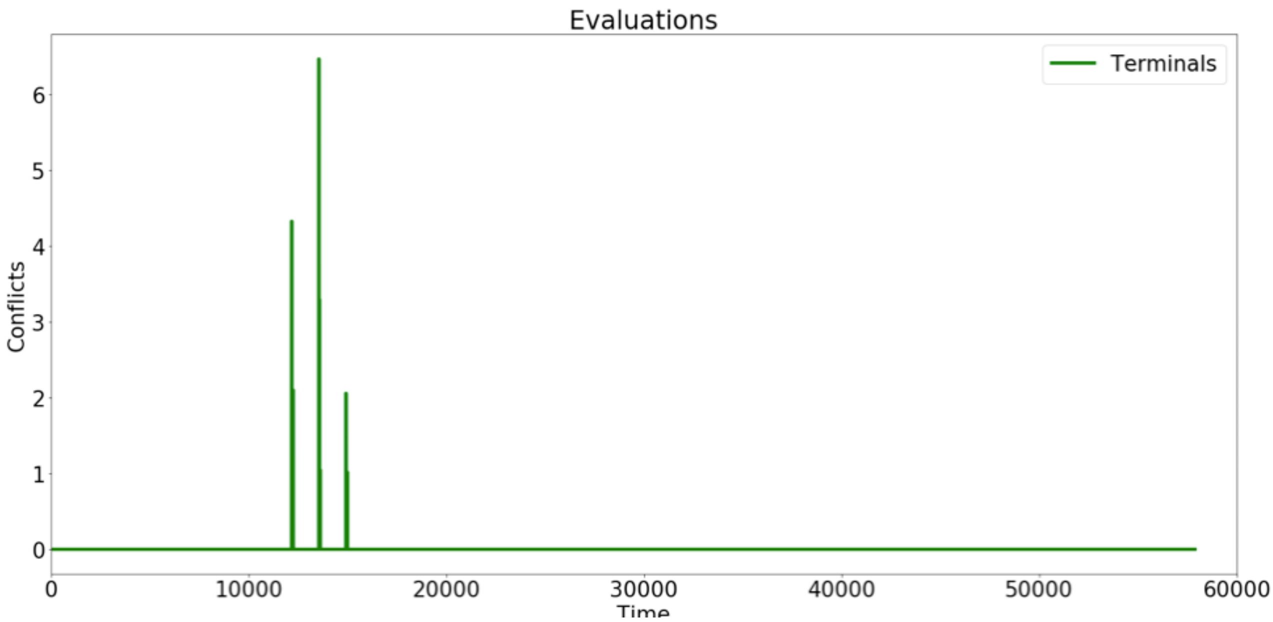


*Figure 13 Evaluation terminal conflicts for the operation day.*

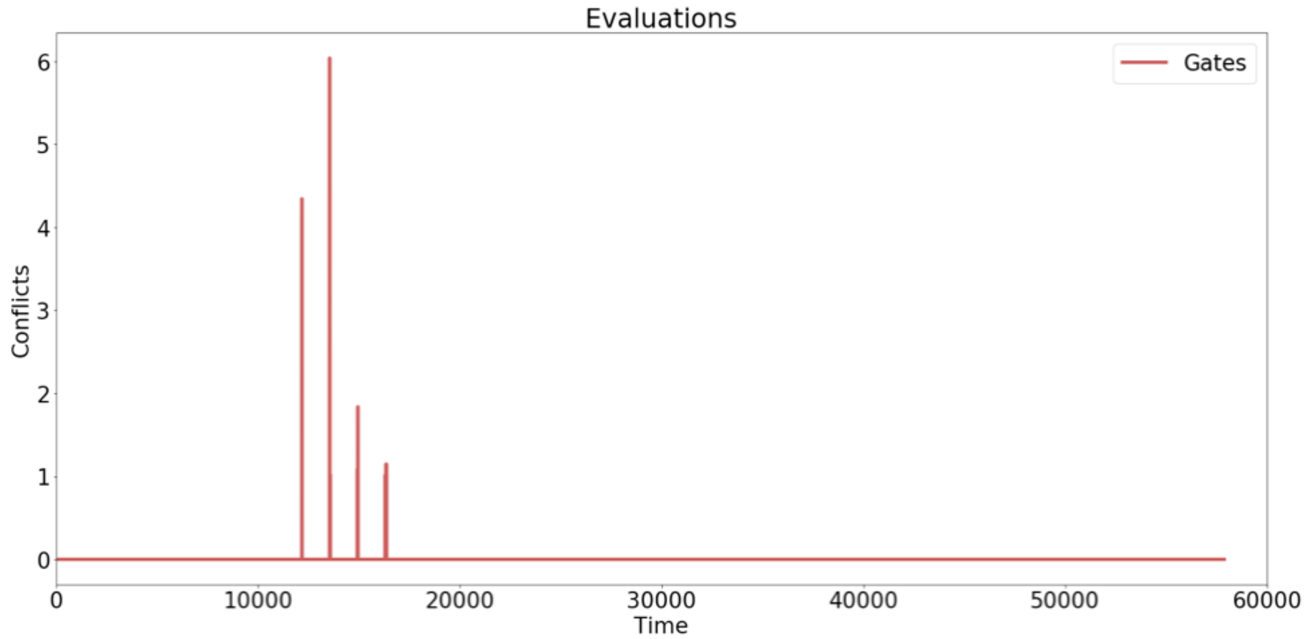


*Figure 14 Evaluation Gates conflicts for the operation day.*

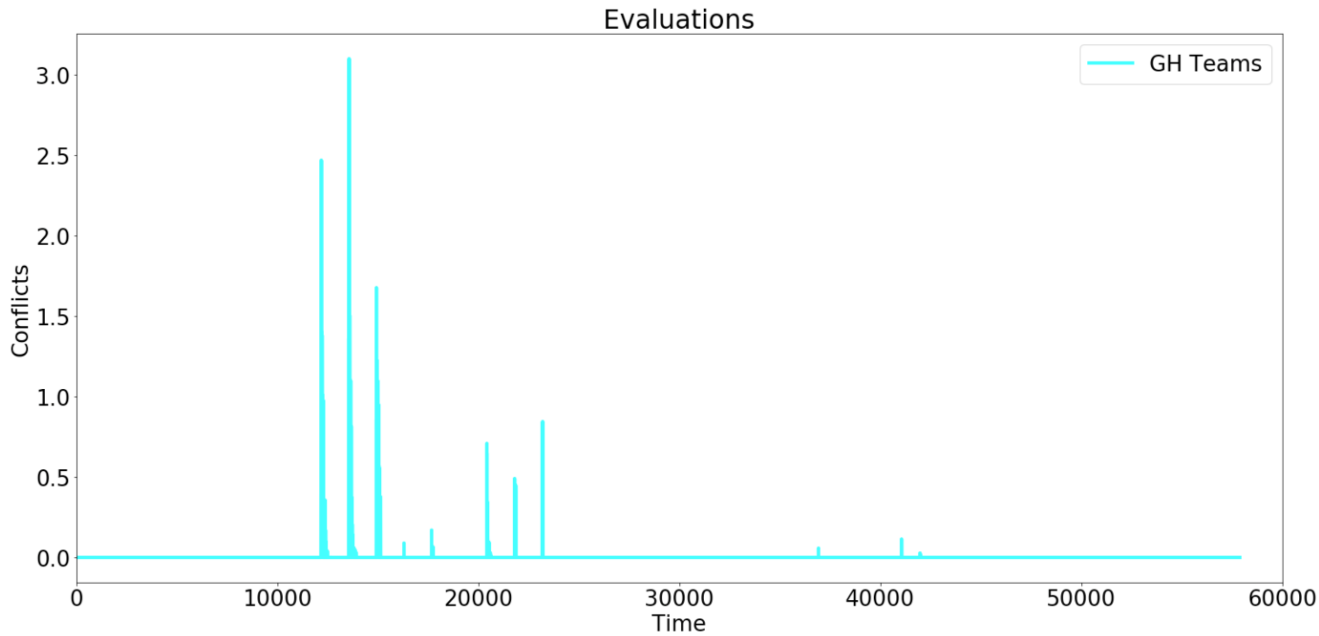


*Figure 15 Evaluation Ground Handling Teams conflicts for the operation day.*

A focus on the part of the day which has with the highest number of conflicts (that is during the morning) is given. We extracted the part of the day with the major demand, it is from 6am to 12pm. The peak hour is between 6 am and 10 am with a total of 332 flights, where 177 were departures, 155 were arrivals and 109 were arrival-departures. We have in total 67 Heavy, 265 Medium and 0 Light aircraft.

The most relevant decisions that we need to focus on are the speed and delay (Figure 16) mainly because the delay is the general objective of our problem we want to reduce. We can easily see that the evaluation of the speed and the delay follow the same pattern and have the major conflicts in the same windows.

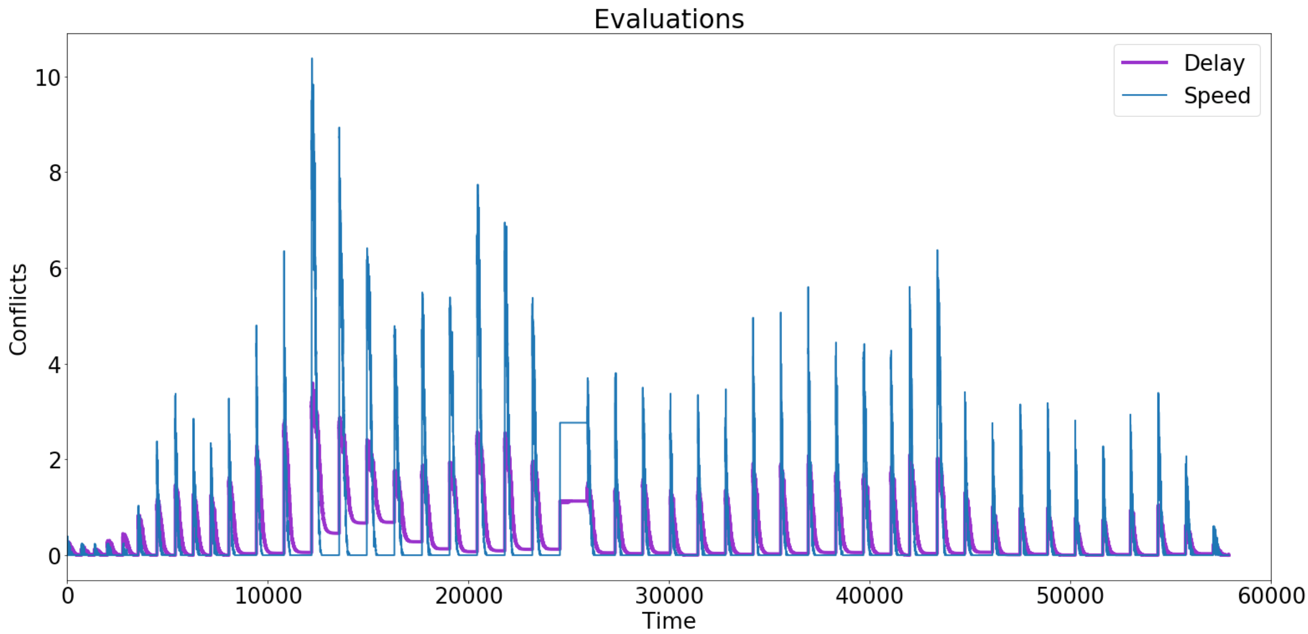


*Figure 16 Evaluation Delay and Speed. The delay is the objective.*

Regarding to the number of ground handling teams the standard model considered 100 ground handling teams with a range of minimum 100 and maximum 150 teams, we stressed the system creating scenarios with different number of teams and we found that the minimum of ground handling teams required to this airport (CDG) in particular is 10 teams, but the operation has a lot of delays due to the lack of ground handling services and the number of conflicts increased a lot. The main key performance indicators the evaluation of the runways (Figure 11), terminals (Figure 13), gates (Figure 14) ground handling teams (Figure 15) and the speed and delay (Figure 16) have the busiest and more number of conflicts during the morning. As an improvement to make the framework more realistic the ground handling teams need to be dynamic depending the number of aircraft and operations on the sliding windows.

## 10. Conclusions and look ahead

This tool is a Decision Support System that is useful for the APOC on the tactical phase to manage the arrival, surface, and departure problems at the macroscopic level, to solve different conflicts related to the terminal airspace in the day of operations, minimize the delays, to reduce airside capacity overload and optimize the different decision variables of each module (runway, speed, gates, and ground handling teams). A good remark is that using the approach that combines optimization and simulation it is possible to obtain efficient solutions that are feasible and robust. The work that is still in progress and will be included in the thesis are the ones that includes the passengers with the terminal security screening.

As part of future work, we would like to improve the model and make it more realistic we would like to optimize the connecting flights and passengers. Also, some simulation scenarios to stress the system. As the framework built is quite general this can easily apply to different days and moreover, to different airports.

# 11. References

## 11.1 Link to PhD thesis / repository

https://hal-enac.archives-ouvertes.fr/search/index

## 11.2 Associated outputs and publications

Sashiko Shirai Reyna, Miguel Antonio Mujica Mota, Daniel Delahaye, José Manuel Ortiz Castro. Modelling and Simulation of APOC Operations. *ICRAT 2020, 9th International Conference for Research in Air Transportation*, Jun 2020, Tampa, United States. ⟨hal-02873356⟩

Sashiko Shirai Reyna, Daniel Delahaye, Miguel Antonio Mujica Mota, José Maria. Improvement of APOC Operations by using Simulation and Experimental Economics: Conceptual Approach. *EMSS 2020, 32nd European Modeling & Simulation Symposium*, Sep 2020, Virtual event, France. pp.207-213/ISBN: 978-88-85741-44-7, ⟨10.46354/i3m.2020.emss.029⟩. ⟨hal-03094829⟩

## 11.3 References cited in this report

Bayram, H., Sahin, R., 2013. A new simulated annealing approach for travelling salesman problem. Mathematical and Computational Applications 18, 313–322. URL: http://www.mdpi.com/2297-8747/18/3/313, doi:10.3390/mca18030313.

Chaimatanan, S., Delahaye, D., Mongeau, M., 2014. A hybrid meta-heuristic optimization algorithm for strategic planning of 4D aircraft trajectories at the continental scale. IEEE Computational Intelligence Magazine 9, 46–61. doi:10.1109/MCI.2014.2350951.

Chams, M., Hertz, A., de Werra, D., 1987. Some experiments with simulated annealing for coloring graphs. European Journal of Operational Research 32, 260 – 266. URL: http://www.sciencedirect.com/science/article/pii/S0377221787801480, doi: http://dx.doi.org/10.1016/S0377-2217(87)80148-0.

Crama, Y., Schyns, M., 2003. Simulated annealing for complex portfolio selection problems. European Journal of Operational Research 150, 546–571.

Deau, R., Gotteland, J.B., Durand, N., 2009. Airport surface management and runways scheduling, in: 8th USA/Europe Air Traffic Management Research and Development Seminar.

Emden-Weiner, T., Proksch, M., 1999. Best practice simulated annealing for the airline crew scheduling problem. Journal of Heuristics 5, 419–436.

EUROCONTTROL, 2018. Airport Network Integration Concept for establishment of an Airport Operations Plan (AOP).

Günther, Y., Inard, A., Werther, B., Bonnier, M., Spies, G., Marsden, A., Temme, M., Böhme, D., Lane, R., Niederstraßer, H., 2006. Total Airport Management (operational concept and logical architecture).

Hanafi, R., Kozan, E., 2014. A hybrid constructive heuristic and simulated annealing for railway crew scheduling. Computers & Industrial Engineering 70, 11–19. URL: https://eprints.qut.edu.au/66685/, doi:10.1016/j.cie.2014.01.002.

Islami, A., Chaimatanan, S., Delahaye, D., 2017. Large-scale 4D trajectory planning, in: Institute, E.N.R. (Ed.), Air Traffic Management and Systems II. Springer Japan. volume 420 of Lecture Notes in Electrical Engineering, pp. 27–47.

Jan Evler, Ehsan Asadi, H.P.H.F., 2021. Airline ground operations: Schedule recovery optimization approach with constrained resources. Transportation Research Part C: Emerging Technologies 128, 103129.

Khadilkar Harshad, B.H., 2016. Integrated control of airport and terminal airspace operations. IEEE Transactions on Control Systems Technology 24, 216–225.

Kirkpatrick, S., Gelatt, C, D., Vecchi, M., 1982. Optimization By Simulated Annealing. IBM Research Report RC 9355. Acts of PTRC Summer Annual Meeting.

Kjenstad, D., Mannino, C., Nordlander, T., Schittekat, P., Smedsrud, M., 2013. Optimizing AMAN-SMAN-DMAN at Hamburg and Arlanda airport. doi:10.13140/2.1.3988.0964.

Lee, H., Balakrishnan, H., 2012. A comparison of two optimization approaches for airport taxiway and runway scheduling, in: Digital Avionics Systems Conference (DASC), 2012 IEEE/AIAA 31st.

Ma, J., Delahaye, D., Sbihi, M., Mongeau, M., 2016a. Integrated optimization of terminal manoeuvring area and airport. Proceedings of the SESAR Innovation Days 2016.

Ma, J., Delahaye, D., Sbihi, M., Mongeau, M., 2016b. Merging flows in terminal maneuvering area using time decomposition approach, in: ICRAT2016, 7th International Conference on Research in Air Transportation.

Ma, J., Delahaye, D., Sbihi, M., Scala, P., 2018. Integrated optimization of arrival, departure, and surface operations, in: ICRAT 2018, 8th International Conference for Research in Air Transportation.

Ma, J., Delahaye, D., Sbihi, M., Scala, P., Mota, M.A.M., 2019a.Integrated optimization of terminal maneuvering area and airport at the macroscopic level. Transportation Research Part C: Emerging Technologies 98, 338–357.

Ma, J., Delahaye, D., Sbihi, M., Scala, P., Mota, M.M., 2017a. A study of tradeoffs in airport coordinated surface operations, in: EIWAC 2017, 5th ENRI international workshop on ATM/CNS.

Ma, J., Sbihi, M., Delahaye, D., 2019b. Optimization of departure runway scheduling incorporating arrival crossings. International Transactions in Operational Research Doi: https://doi.org/10.1111/itor.12657.

Mahmudy, W., 2014. Improved simulated annealing for optimization of vehicle routing problem with time windows (VRPTW). Kursor Journal 7, 109–116. URL: https://kursorjournal.org/index.php/kursor/article/view/36.

Pavese, G., Bruglieri, M., Rolando, A., Careri, R., 2017. Dman-sman-aman optimisation at Milano Linate airport.

Scala, P.M., Mujica, M., Delahaye, D., Ma, J., 2019. A generic framework for modelling airport operations at a macroscopic level, in: Winter simulation conference 2019, Washington, United States. URL: https://hal-enac.archives-ouvertes.fr/hal-02311539.

Scala, P.M., Mujica Mota, M.A., Ma, J., Delahaye, D., 2020. Tackling Uncertainty for the Development of Efficient Decision Support System in Air Traffic Management. IEEE Transactions on Intelligent Transportation Systems 21, pp. 3233–3246. URL: https://hal-enac.archives-ouvertes.fr/hal-02166833, doi:10.1109/TITS.2019.2924981.

Siarry, P., Berthiau, G., Durdin, F., Haussy, J., 1997. Enhanced simulated annealing for globally minimizing functions of many continuous variables. ACM Transactions on Mathematical Software 23, 209–228. URL: http://doi.acm.org/10.1145/264029.264043, doi:10.1145/264029.264043.

Szabo, S., Pilat, M., Makó, S., Korba, P., Čičváková, M., Kmec, 2021. Increasing the efficiency of aircraft ground handling—a case study. Aerospace 9, 2. doi:10.3390/aerospace9010002.

Wong, D., Leong, H., Liu, C., 1988. Simulated annealing for VLSI design. Kluwer.

ACI (Airports Council International) (2017), New study reveals consumers paying higher air fares at congested airports. 25 January, Press Release, https://www.aci-europe.org/press-release/118-new-study-reveals-consumers-paying-higher-air-fares-at-congested-airports.html.

ATW (2016), Air Transport World. July/August 2016. Penton Media, p. 49. http://atwonline.com/datasheet/atw-2016-world-airline-report-top-50-airports-2015.

Banks J., J.S. Carson and B.L. Nelson (1996), *Discrete-Event System Simulation*, 2nd ed., Prentice-Hall.

Burnham, D.C., J.N. Hallock and G.C. Greene (2001), "Increasing airport capacity with modified IFR approach procedures for close-spaced parallel runways". *Air Traffic Control Quarterly*, Vol. 9/1, pp. 45-58.

EUROCONTROL (European Organization for the Safety of Air Navigation) (2013), Challenges of Growth 2013. The Effect of Air Traffic Network Congestion in 2035, pp. 3 and 23. https://www.eurocontrol.int/sites/default/files/content/documents/official-documents/reports/201310-challenges-of-growth-2013-task-6.pdf.

European Union (2014), The EU explained: Transport. ISBN 978-92-79-42777-0, p. 18. https://europa.eu/european-union/topics/transport_en.

Hamzawi, S.G. (1992), "Lack of airport capacity: Exploration of alternative solutions". *Transportation Research: An International Journal Part A: Policy and Practice*, No. 1. pp. 47-58. Pergamon Press, pp. 47-58.

Henrisken, J.O. (1983), "The Integrated Simulation Environment", *Operations Research*, Vol. 31/6.

Herrera García, A. and E. Moreno-Quintero (2011), "Strategy for attending takeoffs and landings to reduce the aircraft operating costs and the passenger delays". *European Journal of Transport and Infrastructure Research*. Vol. 11/2, pp. 219-233. https://journals.open.tudelft.nl/ejtir/article/view/2923.

ICAO (1996), Procedures for Air Navigation Services. Rules of the Air and Air Traffic Services (PANS-RAC). Doc. 4444-RAC/501. Part V, Section 16 and Part VI, Section 7.

Mica, J.L. (2015), U.S. Airports in Crisis. United States House of representatives. Congressional Staff Report, pp. 4, 5 and 7. https://mica.house.gov/uploads/Airports%20in%20Crisis%20W-Mica%20Edits%202%20FINAL.pdf.

Rossow, V.J. and L.A. Meyn (2008), "Guidelines for Avoiding Vortex Wakes During Use of Closely-Spaced Parallel Runways". NASA Ames Research Center, Moffett Field, California.

Kazda, A., and Caves, R. E. 2007. Airport Design and Operation. Elsevier, Oxford, UK.

Zografos, K. G., and Madas, M. A. 2007. Advanced Modeling Capabilities for Airport Performance Assessment and Capacity Management. J. of Transportation Research Board, 2007, Transportation Research Board of the National Academies, Washington, D.C., 60-69.

Baik, H., Sherali, H. D., and Trani, A. A. 2002. Time-Dependent Network Assignment Strategy for Taxiway Routing at Airports. J. of the Transportation Research Board, 1788, Transportation Research Board of the National Academies, Washington, D.C., 70-75.

Martinez, J. C., Trani, A. A., and Ioannou, P. G. 2001. Modeling Airside Airport Operations Using General-Purpose, Activity-Based, Discrete-Event Simulation Tools. J. of the Transportation Research Board, 1744, Transportation Research Board of the National Academies, Washington, D.C., 65-71.

Simmod Manual – How Simmod Works. US Federal Aviation Administration. http://www.tc.faa.gov/acb300/how_simmod_works.pdf.

MIDAS: Man-Machine Integration Design and Analysis System. NASA. https://humansystems.arc.nasa.gov/groups/midas/index.html.

Chiu, C. Y., and Walton, C. M. 2002. Integrated Simulation Method to Evaluate the Impact of New Large Aircraft on Passenger Flows at Airport Terminals. J. of the Transportation Research Board, 1788, Transportation Research Board of the National Academies, Washington, D.C., 83-92.

Ferber, J. 1999. Multi-Agent Systems: An Introduction to Distributed Artificial Intelligence. Addison Wesley, Harlow, UK.

Bando, M., Hasebe, K., Nakayama, A., Shibata, A., and Sugiyama, Y. 1995. Dynamic model of traffic congestion and numerical simulation. Physical Review, E51, 1035-1042.

Nakamura, Shun & Furuta, Kazuo & Kanno, Taro & Yoshihara, Shigeki & Mase, Takamichi. (2010). Multi -Agent simulation of ground aircraft operations at a large airport. 10.4108/ICST.SIMUTOOLS2010.8724.

Martinez, Julio & Trani, Antonio & Ioannou, Photios. (2001). Modeling Airside Airport Operations Using General-Purpose, Activity-Based, Discrete-Event Simulation Tools. Transportation Research Record. 1744. 65-71. 10.3141/1744-08.

Xiong Li, Xiaoqing Chen. Airport Simulation Technology in Airport Planning, Design and Operating Management. Applied and Computational Mathematics. Vol. 7, No. 3, 2018, pp. 130-138. doi: 10.11648/j.acm.20180703.18.

Monechi B, Servedio VDP, Loreto V (2015) Congestion Transition in Air Traffic Networks. PLoS ONE 10(5): e0125546. https://doi.org/10.1371/journal.pone.0125546.

Nicole Adler, Eran Hanany, and Stef Proost. 2014. "Managing European air traffic control provision". Fourth SESAR Innovation Days, 25th–27th November. https://nicoleadler.huji.ac.il/publications/managing-european-air-traffic-control-provision.

Katz M. L. and Shapiro C., "Technology adoption in the presence of network externalities", Journal of Political Economy, vol. 94, pp. 822- 841, 1986.

Zhang Q., Han B. and Lu F., "Simulation model of passenger behavior in transport hubs", *2009 International Conference on Industrial Mechatronics and Automation*, Chengdu, 2009, pp. 220-224.

EUROCONTROL Long-Term Forecast – Flight Movements 2010 to 2030, https://www.eurocontrol.int, 2010.

Performance Review Committee. US / Europe comparisons of ATM operational and economic performance. Eurocontrol/FAA, 2013.

Button K. and Neiva R., "Single European Sky and the functional airspace blocks: Will they improve economic efficiency?" Journal of Air Transport Management, vol. 33, pp. 73-80, 2013.

Cook A., European Air Traffic Management: Principles, Practice, and Research. Ashgate Publishing, Ltd., 2007.

Poole R., Developments in Air Transportation. Annual Privatization Report, Reason Foundation, 2013.

McDougall G. and Roberts A., "Commercializing Air Traffic Control: have the reforms worked?" Canadian Public Administration, vol. 51, pp. 45-69, 2008.

EUROCONTROL, "Performance Review Report: An assessment of air traffic management in Europe during the calendar year 2012". Performance Review Commission, 2013.

Button K. and McDougall G., “Institutional and structure changes in air navigation service-providing organizations”. Journal of Air Transport Management, vol. 12, pp. 236–252, 2006.

Huet F., Achieving the Single European Sky: Goals and Challenges. Wolters Kluwer, 2011.

ITA, “Cost of air transport delay in Europe”, Institut du Transport Aérien, 2000.

University of Westminster, *“*European airline delay cost reference values”. Performance Review Unit, Eurocontrol, 2011.

Castelli L., Debels P. and Ukovich W., “Route-charging policies for a central European cross-border upper airspace”, Journal of Air Transport Management, vol. 11, pp. 432-441, 2005.

Raffarin M., “Congestion in European airspace: A pricing solution?” Journal of Transport Economics and Policy, vol. 38, pp. 109-126, 2004.

Jovanović R., Tošić V., Čangalović M. and Stanojević M., “Anticipatory modulation of air navigation charges to balance the use of airspace network capacities”. Transportation Research Part A: Policy and Practice, vol. 61, pp. 84-99, 2014.

Starkie D., “Reforming UK airport regulation”. Journal of Transport Economics and Policy, vol. 35, pp. 119-135, 2001.

Adler N. and Liebert V., “Joint impact of competition, ownership form and economic regulation on airport performance and pricing”. Transportation Research Part A: Policy and Practice, vol. 64, pp. 92-109, 2014.

Gatersleben M. R. and Van der Weij S. W., *“*Analysis and simulation of passenger flows in an airport terminal,*” WSC'99. 1999 Winter Simulation Conference Proceedings. ‘Simulation - A Bridge to the Future’ (Cat. No.99CH37038),* Phoenix, AZ, USA, 1999, pp. 1226-1231 vol.2. doi: 10.1109/WSC.1999.816845.

Groppe M. and Bui M., “Study of Cockpit’s Perspective on Human-Human Interactions to Guide Collaborative Decision Making Design in Air Traffic Management,” *First International Conference on Advances in Computer-Human Interaction*, Sainte Luce, 2008, pp. 107-113. doi: 10.1109/ACHI.2008.51.

Corker K. M., “Human performance simulation in the analysis of advanced air traffic management”, *WSC’99. 1999 Winter Simulation Conference Proceedings. ‘Simulation - A Bridge to the Future’ (Cat. No.99CH37038),* Phoenix, AZ, USA, 1999, pp. 821-828 vol.1. doi: 10.1109/WSC.1999.823293.

Boril J., Jalovecky R. and Ali R., “Human-machine interaction and simulation models used in aviation”, *Proceedings of 15th International Conference MECHATRONIKA*, Prague, 2012, pp. 1-4.

Kagel, J.H., Roth A. E., “The Handbook of Experimental Economics”, Vol 2., Princeton University Press, 2016.

Friedman D., Sunder S., “Experimental Methods: A Primer for Economists”, Cambridge University Press, 1994.

AIRBUS, “Global Market Forecast Growing Horizon 2017-2036”, AIRBUS, Blagnac Cedex, France, Ref, D14029465, April 2017.

OAG, “OAG punctuality league”, OAG, www.oag.com, Jan. 2018.

ICAO, “Air Traffic Management”, ICAO, Doc. 4444, 2007.

ICAO, “Aircraft Operations”, ICAO, Vol. 1 Flight procedures Doc. 8168, 2006.

North M.J., Macal C., 2007 “Managing Business Complexity: Discovering Strategic Solutions with Agent-based Modelling and Simulation”, Oxford U. Press.

EUROCONTROL CDM-TF, Airport CDM Implementation – The Manual, EUROCONTROL, Brussels 2005

APOC, EUROCONTROL, 2018.

Grether D., Fürbas S., Nagel. K., 2013, "Agent-based Modelling and Simulation of Air Transport Technology", Procedia Computer Science, Vol.19, pp. 821-828.

Bouarfa, S., Müller, J.S., Blom, H.A. 2018. "Evaluation of a Multi-Agent System approach to airline disruption management", Journal of Air Transport Management, Vol. 71, pp. 108-118.

Bouarfa, S., Blom, H., Curran R., 2012, "Airport Performance Modelling using and agent based approach", in Proc. of 3rd ATOS2012, Delft, The Netherlands.

Bouarfa, S., Blom, H., Curran R., 2018, "Agent-based modelling and Simulation of Coordination by Airline Operations Control", IEEE Transactions on Emerging Topics in Computing.

Metcalfe, Robert & Dolan, Paul, 2012. "Behavioural economics and its implications for transport", Journal of Transport Geography, Elsevier, vol. 24(C), pages 503-511.

Markovits-Somogyi, Rita & Aczel, Balazs. (2013). Implications of Behavioural Economics for the Transport Sector. Periodica Polytechnica Transportation Engineering. 41. 65. 10.3311/PPtr.7101.

Gillen, D., & Lall, A. (1997). Developing measures of airport productivity and performance: an application of data envelopment analysis. Transport Res - Part E, 33 (4), 261–273.

Graham, A., & Metz, D. (2017). Limits to air travel growth: The case of infrequent flyers. Journal of Air Transport Management, 62, 109–120.

Günther, Y., Inard, A., Werther, B., Bonnier, M., Spies, G., Marsden, A., Eriksen, P. (2006). Total Airport Management: Operational Concept & Logical Architecture., 44. http://www.bs.dlr.de/tam/Dokuments/TAM-OCD-public.pdf.

Classen, A. B. (2012). Total Airport Management Suite Passenger in focus Improved integration of airside and landside processes. http://www.tams.aero/documents/abschlusspresentation/TAMS Dissemination Event 08 Classen 20120522.pdf.

Cook, A., Tanner, G., Jovanovic, R., & Lawes, A. (2009). The cost of delay to air transport in Europe - Quantification and management. In Air transport research society world conference. Abu Dhabi. https://westminsterresearch.westminster.ac.uk/item/90w7x/the-cost-of-delay-to-air-transport-in-europe-quantification-and-management.

Papenfuss, A., Carstengerdes, N., Schier, S., & Günther, Y. (2017). What to say when: Guidelines for Decision Making An evaluation of a concept for cooperation in an APOC. In 12th USA/Europe air traffic management research and development seminar (p. 11). Seattle, USA. https://drive.google.com/file/d/1CaJmhJAzIkQV4ZeaqXKBGosbrlysDOX7/view.

Spies, G., Piekert, F., Marsden, A., Suikat, R., Meier, C., & Eriksen, P. (2008). Operational concept for an airport operations center to enable total airport management. In 26th international congress of the aeronautical sciences (p. 10). Anchorage, USA. http://icas.org/ICAS_ARCHIVE/ICAS2008/PAPERS/535.PDF.

# Annex I: Acronyms

| Term | Definition |
|---|---|
| A-CDM | Airport Collaborative Decision Making |
| AMAN | Arrival Management |
| AOP | Airport Operation Plan |
| APOC | Airport Operation Centre |
| ATCO | Air Traffic Control Officer |
| ATM | Air Traffic Management |
| CDG | Charles de Gaulle Airport |
| CTOT | Computed Take-Off Time |
| DCB | Demand Capacity Balancing |
| DMAN | Departure Management |
| DSS | Decision Support System |
| GH | Ground Handling |
| KPI | Key Performance Indicator |
| MET | Meteorological Services |
| NOP | Network Operation Plan |
| RCPSP | Resource-Constrained Project Scheduling Problem |
| RTA | Required Time of Arrival |
| SA | Simulated Annealing |
| SESAR | Single European Sky's ATM Research |
| SID | Standard Instrument Departure |
| SMAN | Surface Management |
| STAR | Standard Terminal Arrival Routes |
| TAM | Total Airport Management |
| TMA | Terminal Manoeuvring Area |
| TOBT | Target Off-Block Time |
| TTOT | Target Take-Off-Time |