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Integrated Optimization of Terminal Maneuvering Area and Airport

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***Abstract*—Airports and surrounding airspaces are limited in terms of capacity and represent the major bottleneck in the air traffic management system. This paper addresses the problems of airspace conflicts and airport congestion at a macroscopic level through the integrated control of arrivals and departures. Conflict detection and resolution methods are applied to a predefined terminal route structure. Different airside components are modeled 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 is proposed to solve the corresponding problem. Computational experiments performed on real-world case studies of Paris Charles De-Gaulle airport, show the benefits of this macroscopic level approach.**

I. Introduction

With the steady growth of air traffic demand, airport surfaces and surrounding terminal airspaces become more and more congested, thus causing significant delays and operational costs, especially at major airports. Therefore, the efficient planning of airport and terminal area operations is critical for mitigating these negative impacts.

In the past years, segregated research on arrival management [1, 2], departure management [3, 4] and surface problems [5–7] have been conducted. These tools have already demonstrated that they can lead to improved safety and efficiency [8]. Recently, more efforts are made on integrated optimization models for airside (runway, taxiway and terminal) and airspace (terminal airspace) operations.

New technologies integrating existing optimization support systems in order to act as holistic decision-support tools for all airport partners are proposed (TAM: Total Airport Management [8]). Several integrated problems have been defined and studied in the literature. In [9, 10], taxiway and runway schedules are optimized and ground traffic simulations carried out to compare with the optimization results. In [11], 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 aim of our study is to integrate airports and terminal airspace at a macroscopic level taking into account some operational restrictions and airport resources constraints.

The remainder of this paper is structured as follows. Section II describes the problem and models terminal operations and airport network congestion control. Section III presents the solution approach. Section IV performs experiments and analyzes the results. Section V gives some conclusions and perspectives.

II. Problem description and model

In the terminal airspace, aircraft from different entry points must be merged and sequenced into an orderly stream, then prepare to land at the runway. After slowing down the speed and vacating the runway, aircraft taxi in to the assigned gate. Then, after a certain turnaround duration for disembark, embark and other ground-holding operations, aircraft push back, taxi out and depart again.

Due to different anticipation time of airspace, runway and ground traffic situations, considering specifically various levels of abstraction is critical for the planning. For example, two hours before landing, aircraft arrival is still subject to so much uncertainty in the airspace, that the detail of what is happening on the taxiway is not relevant. The airport components (terminals, taxi network) can be globally modeled seen as simple nodes with specific capacities. There is not yet need to specify a flight-by-flight level of detail on the ground. However, five minutes before landing, the ground traffic situation and the gate occupancy become more important for aircraft to find a shortest time to taxi-in and to taxi-out. These two situations represent a macroscopic and a microscopic level for airport planning.

Our first step is to consider the terminal and airport integration problem at a macroscopic level, in order to be sufficiently flexible to resolve airspace conflicts, to mitigate airport congestions and to ensure feasibility.

A. Network model of TMA and airport surface

Our TMA route model uses the same classical node-link network introduced in [12]. We assume that a route network graph, or to be more precise as a tree here, $G(\mathscr{N}, \mathscr{L})$, in which the aircraft are allowed to fly in TMA airspace, is given, where $\mathscr{N}$ is the node set and $\mathscr{L}$ is the link set. Each *route* is defined by a succession of nodes and links; the first link starts from an entering point, and the last link ends at the runway threshold. Each aircraft follows exactly one of these routes corresponding to its entering point.

Fig. 2 displays a model example of a route network: Paris Charles De-Gaulle (CDG) airport two landing runways, 26L and 27R. In the arrival procedure, four routes fuse into one single route towards one runway. Each of the starting nodes of these four routes is a so-called Initial Approach Fix (IAF).

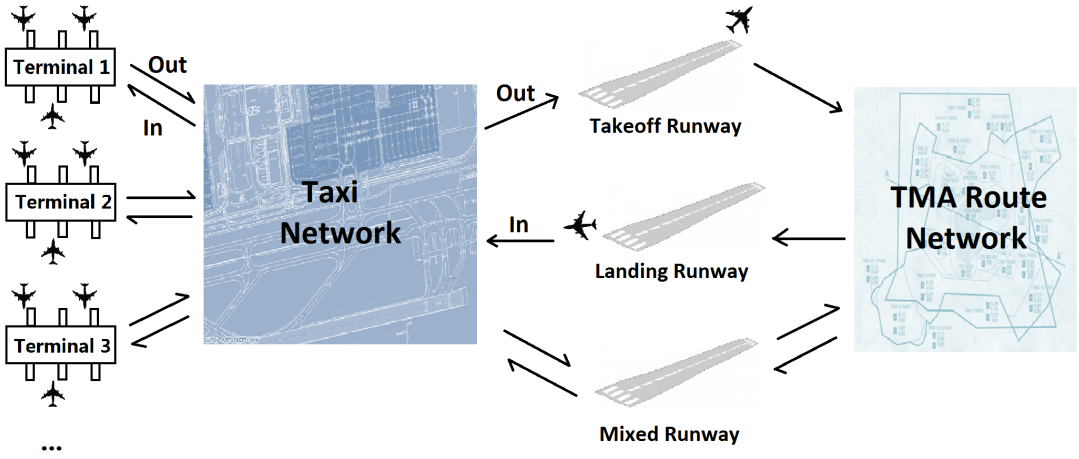
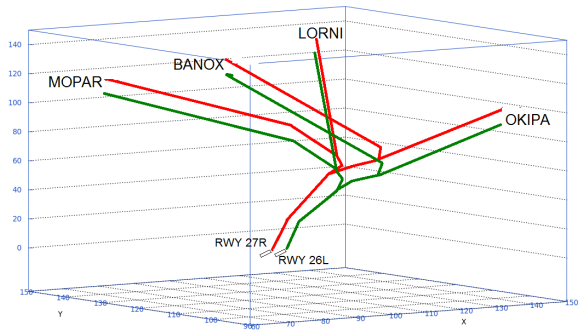
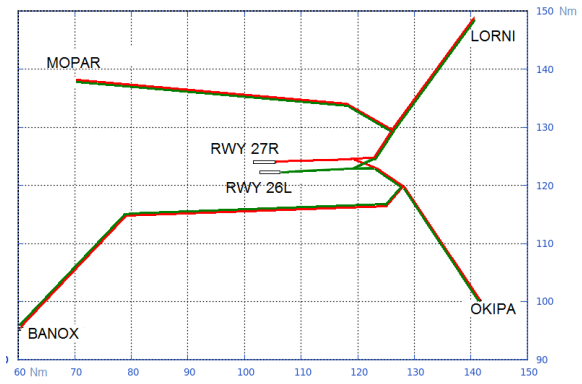


Figure 1. Network model of TMA and airport surface



(a) Arrival route structure, 3D view



(b) Arrival route structure, 2D view

Figure 2. Arrival route structure model example

The set of entering points here is N_e = { MOPAR, LORNI, OKIPA, BANOX }.

Different components of airport are considered using a network abstraction. Runways and terminals are modeled as resources with a specific capacity. We only take into account the overall capacity of a terminal without considering its individual gates. Taxiway is seen as a network with a threshold of total allowed number of taxi-in and taxi-out aircraft. The network model of TMA and airport surface is illustrated in Fig 1.

B. Given data

Assume that we are given a set of flights (or aircraft), $\mathcal{F} = \{1, \ldots, N_f\}$. Each flight can be in one of three operations: $\mathcal{F} = \{\mathcal{A}, \mathcal{AD}, \mathcal{D}\}$, where $\mathcal{A}$ stands for arrival, $\mathcal{AD}$ for arrival-departure and $\mathcal{D}$ for departure. Flights that land at the airport and stay until the end of the day are said to be arrival. When an aircraft arrives at the airport and departs again after a turnaround duration, it is arrival-departure. Flights that park at the airport at the beginning of the day and depart later are tagged as departure.

For each flight $f \in \mathcal{F}$, the following data is given:

- C_f: wake turbulence category ($f \in \mathcal{F}$);
- M_f: assigned terminal number ($f \in \mathcal{F}$);
- E_f: entering waypoint number at TMA ($f \in \mathcal{A} \bigcup \mathcal{AD}$);
- T_f^0: initial RTA (Required Time of Arrival) at the entering waypoint of TMA ($f \in \mathcal{A} \bigcup \mathcal{AD}$);
- V_f^0: initial speed at the entering waypoint of TMA ($f \in \mathcal{A} \bigcup \mathcal{AD}$);
- T_f^{in}: taxi-in duration ($f \in \mathcal{A} \bigcup \mathcal{AD}$);
- P_f^0: earliest off-block time ($f \in \mathcal{D} \bigcup \mathcal{AD}$);
- T_f^{out}: taxi-out duration ($f \in \mathcal{D} \bigcup \mathcal{AD}$);
- R_f^d: departure runway number ($f \in \mathcal{D} \bigcup \mathcal{AD}$);

Earliest off-block time 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:

- Taxi-in and taxi-out duration for each aircraft is an average value depending on the terminal and runway. Table I and II show respectively an example of these two durations at Paris CDG airport that we will use in this paper.
- Each aircraft reduces its speed with a constant deceleration in TMA.
- Aircraft landing time is calculated based on the length of its TMA route, the actual RTA and the above constant deceleration.

TABLE I
AVERAGE TAXI-IN DURATION ACCORDING TO TERMINAL AND RUNWAY (IN SECONDS)

Landing runway	Terminal 1	Terminal 2	Terminal 3
27R	400	730	680
26L	535	500	530

TABLE II
AVERAGE TAXI-OUT DURATION ACCORDING TO TERMINAL AND RUNWAY (IN SECONDS)

Takeoff runway	Terminal 1	Terminal 2	Terminal 3
27L	720	890	880
26R	1400	760	710

- In-block time = actual landing time + runway occupancy time + average taxi-in duration.
- Takeoff time = actual off-block time + average taxi-out duration.
- Flights are assumed to be able to park at any gates in their assigned terminal.

C. Decision variables

The optimization model we are using features four types of decision variables:

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

$$\mathcal{T}_f = \{T_f^0 + j\Delta T \,|\Delta T_{\min}/\Delta T \leqslant j \leqslant \Delta T_{\max}/\Delta T,\ j \in \mathbb{Z}\},$$

where ΔT is a discretized time increment, an input parameter whose value is to be set by the user. In order to shift an aircraft entering time at TMA, we can either delay it or speed it up during the en-route procedure. In practice, the latter strategy consumes more fuel, and may be far less interesting for the airlines. As a consequence, our time slot interval is asymmetric, with $|\Delta T_{\max}| \geq |\Delta T_{\min}|$. In this study, we set $\Delta T_{\max} = 30\text{min}$, $\Delta T_{\min} = -5\text{min}$.

2) Entering speed at TMA for $f \in \mathcal{A} \bigcup \mathcal{AD}$: We define an entering speed decision variable $v_f \in \mathcal{V}_f$, where

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

where Δ_f^v is a (user-defined) time increment, $V_f^{\min}$ and $V_f^{\max}$ are given input data corresponding to the minimum and maximum allowable speeds for aircraft f. In this study, we set $V_f^{\min} = 0.9V_f^0$, $V_f^{\max} = 1.1V_f^0$ and $\Delta_f^v = 0.01V_f^0$. We also make sure *a priori* that $V_f^{\max}$ is not exceeding the maximum speed defined by the aircraft type.

3) Landing runway for $f \in \mathcal{A} \bigcup \mathcal{AD}$: $r_f^a \in \mathcal{R}_f$ is the landing runway decision for arrivals. Runway reassignment is used to balance the capacity when one runway gets overloaded while another is still capable to accommodate more aircraft.

4) Pushback delay for $f \in \mathcal{D} \bigcup \mathcal{AD}$: We define a pushback delay decision variable $p_f \in \mathcal{P}_f$, where

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

We can only delay departure aircraft, in this study, we choose the maximum delay to be $\Delta T_{\max}^p = 15\text{min}$, which is a reasonable value in practice.

To summarize, our decision vector is $\mathbf{x} = (\mathbf{t}, \mathbf{v}, \mathbf{r}, \mathbf{p})$, where $\mathbf{t}$ is the vector whose f^{th} component is the decision variable t_f, $\mathbf{v}$ is the vector whose f^{th} component is the decision variable v_f, $\mathbf{r}$ is the vector whose f^{th} component is the decision variable r_f^a, and $\mathbf{p}$ is the vector whose f^{th} component is the decision variable p_f (all of which correspond to flight f).

D. Objectives

The model is designed to resolve conflicts in the air, and to reduce airside capacity overload.

The number of conflicts is evaluated by node and link conflicts detection. The airside capacity overload involves runways, terminals and taxiway network evaluation.

Our objective function, to be minimized is therefore a weighted sum of these functions:

$$\gamma_a A(\mathbf{x}) + \gamma_s S(\mathbf{x})$$

where γ_a and γ_s are weighting coefficients for the total number of conflicts in airspace, $A(\mathbf{x})$ and the airside capacity overload, $S(\mathbf{x})$, respectively. Next, we will introduce precisely how to evaluate the airspace conflicts and the airport congestions.

1) Conflicts detection in the TMA: Considering above-described TMA route network structure, two kinds of conflicts are defined:

- Link conflict: For each given link, we verify twice whether a conflict occurs, *i.e.*, the minimum wake turbulence separation (shown in Table III) is violated: at the entry and at the exit of the link. Moreover, we ensure that the order of sequencing remains the same along the link.

TABLE III
SEPARATION MINIMA ACCORDING TO AIRCRAFT CATEGORIES (IN NM).

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

- Node conflict: If no link conflict is detected, wake-turbulence separation can be guaranteed. However, at the intersection of two successive links, violation of the horizontal separation requirement between any two consecutive aircraft (3 Nm in TMA) may still occur. Therefore, we verify that when an aircraft flies over a node, the horizontal separation with other aircraft is respected.

Note that once the decision variable values are set, we can calculate the corresponding times at which the aircraft passes each node and each link. Then, we use these time values to evaluate the number of link and node conflicts. The conflict detection methodology is described in detail in [12].

2) Congestion evaluation in the airside:

- Runway congestion evaluation: The landing/takeoff time difference of any two consecutive aircraft must respect the time separation. The runway separation rules are calculated by incorporating the different flight velocities and their impact on the final approach segment. Here we use the data of [13], shown in Table IV, where A refers to Arrival and D refers to Departure:

TABLE IV
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***
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	111	120
	D-M	60	60	60	60	60	60
	D-L	60	60	60	60	60	60

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 causes runway congestions. Therefore, we note the accumulated time of separation violation for all pairs of aircraft as an indicator for our runway evaluation. Fig. 3 gives an example of how we measure the time of separation violation.

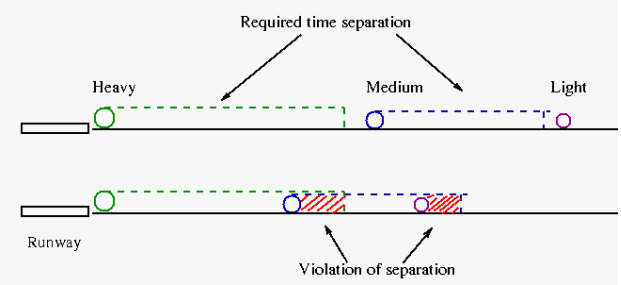


Figure 3. Runway separation example

- Terminal and taxiway congestion evaluation:
We have two metrics to measure the terminal congestion. First, the maximum overload number is calculated based on the difference between the actual total number of aircraft in the terminal and the given terminal capacity. This metric gives us an idea of at what time severe congestion occurs. However, the maximal overload does not provide sufficient information on the level of congestion. Therefore, another important metric is to consider the total amount of time during which aircraft experience congestions in the terminal.

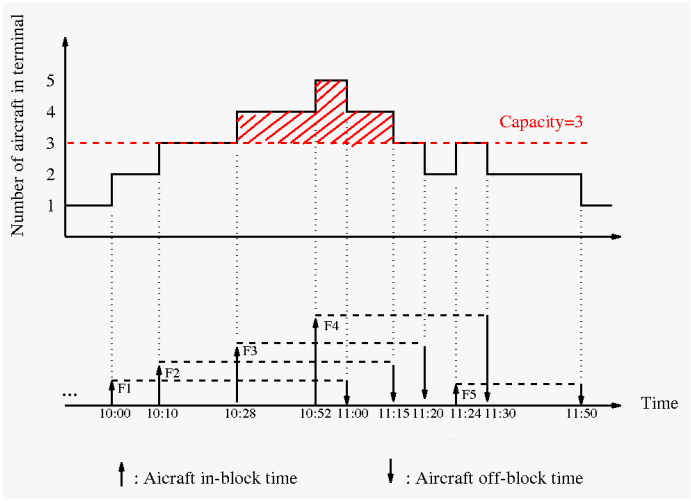


Figure 4. Example of terminal congestion evaluation

Let us consider simple example to show how we propose to measure the terminal congestion level. As illustrated in Fig. 4, suppose that we have one terminal with three gates (i.e., the capacity is 3), and 5 flights turnaround in this terminal. The upward (respectively, down) arrow represents the in-block (off-block) time of one aircraft, linked by a dotted line. We count the cumulated number of aircraft in the terminal as time goes by. Here, the maximal terminal occupancy is 5, therefore the maximal overload is 2. We calculate the total congestion time as well, which is 55 minutes here (the red surface shown in Fig 4).

The taxiway network congestion can be measured in a similar way. We define a maximal allowed number of aircraft in the taxiway network. If the total number of taxi-in and taxi-out aircraft exceeds this saturation point, congestion occurs. We note as well the maximal overload and the total congestion time for taxi network evaluation.

III. SOLUTION APPROACHES

It is known that even the sub-problem of this integrated optimization, aircraft landing scheduling, is NP-hard [1]. This motivates us to use heuristic approach. Moreover, if we consider $|\mathcal{A}| + |\mathcal{D}| + |\mathcal{AD}|$ flights with a number of entry time changes $|\mathcal{T}_f|$, entry speed changes $|\mathcal{V}_f|$, landing runways $|\mathcal{R}_f|$ and pushback delay changes $|\mathcal{P}_f|$, the total number of possible combinations of decision variables is equal to $(|\mathcal{T}_f| * |\mathcal{V}_f| * |\mathcal{R}_f| * |\mathcal{P}_f|)^{|\mathcal{AD}|} + (|\mathcal{T}_f| * |\mathcal{V}_f| * |\mathcal{R}_f|)^{|\mathcal{A}|} + |\mathcal{P}_f|^{|\mathcal{D}|}$. For instance, if $|\mathcal{A}| = 100$, $|\mathcal{D}| = 100$, $|\mathcal{AD}| = 400$, $|\mathcal{T}_f| = 400$, $|\mathcal{V}_f| = 20$, $|\mathcal{R}_f| = 2$ and $|\mathcal{P}_f| = 200$, then there would be more than $(32 * 10^5)^{400}$ possible solutions to be considered. Due to this high combinatorics, we propose a time decomposition approach combined with a simulated annealing algorithm to address the problem.

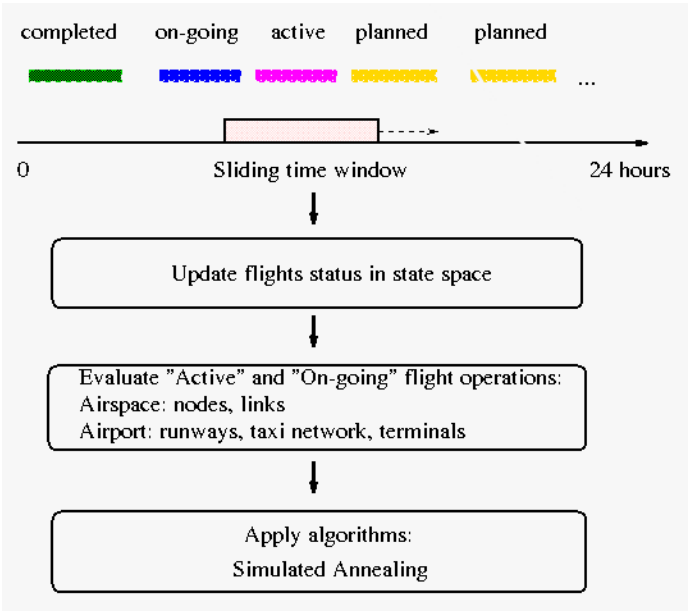


Figure 5. Sliding window approach

A. Time sliding-window decomposition approach

The approach we are proposing addresses the original problem by decomposing it into several sub-problems using a time sliding window in order to reduce the computational burden [12]. This specific approach is generic and can be extended and applied to other real-time operation problems.

Fig. 5 illustrates how sliding window approach works. Each aircraft is classified into four different status: *completed*, *on-going*, *active* and *planned*, based on its operation time interval relative to the sliding window. 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, 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 take into account 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 are updated, a new set of flights waiting to be addressed are considered, and the optimization process is repeated. Detailed description can be found in [12].

B. Simulated annealing

Simulated Annealing (SA) is a meta-heuristic well known for its ability to trap out of local minima by allowing random local changes. Moreover, it can easily be adapted to large-scale problems with continuous or discrete search spaces. We propose a SA algorithm adapted to our problem. First, a neighborhood function is defined to generate a local change from the current solution.

To generate a neighborhood solution, instead of simply choosing randomly a flight f in the active-flight set, we use a method similar to the so-called roulette-wheel selection. We note for each aircraft the number of conflicts and the time of congestion as its *air* and *ground performance* respectively. Air performance involves link and node conflicts, and ground performance involves runway, taxiway network and terminals congestions. For example, in Fig 4, we note the total time during which an aircraft is overlapping with other flights. For example, the overlapping time between flight $F1$ and all the other flights is 50 minutes; for $F5$ is only 6 minutes. The flight terminal performance is reported in Table V:

TABLE V
AN EXAMPLE OF AIRCRAFT TERMINAL PERFORMANCE (IN MIN)

Flight	$F1$	$F2$	$F3$	$F4$	$F5$
Terminal perfo	50	65	52	34	6

Considering its overload period, it is clearly useless to change the decisions involving flight $F5$ in order to mitigate the terminal congestion. The performance metric can help us to better focus on the most charged and congested periods. The fact that our neighborhood definition is based on the air and ground flight performance augments the likelihood that a flight involving many conflicts, or experiencing severe congestions, will be chosen.

IV. Optimization results

We test our methodology on a 24-hour real data case at Paris CDG Airport. Numerical results with different settings of (user-defined) algorithm parameters are presented and discussed. The overall process is run on a 2.50 GHz core i7 CPU, under Linux operating system PC based on a Java code.

A. Real data analysis

We use an actual one-day flight data on 07/02/2016. On this date, a total of 1116 flights were operated at CDG, including 562 departures and 554 arrivals. We have in total 280 Heavy and 836 Medium aircraft. The fleet mix ratio on this day is Heavy:Medium = 25%:75%.

A most frequently used configuration, four parallel runways, two for the departures (26R, 27L) and the other for arrivals (26L, 27R), are in use during the whole day. There are three terminals at CDG. Our model can easily be extended to other airports with different runway configuration and terminals.

The related user-defined parameters for our model, the SA algorithm and the sliding-window approach are empirically determined after several tests to the values shown in Table VI.

B. Conflicts resolution results

Fig. 6 is an example of four sliding windows optimization evolution, it shows the value of the best solution for node and link conflicts found at each temperature step during the cooling process of SA and for each sliding window. After applying the SA algorithm with the parameter settings displayed in

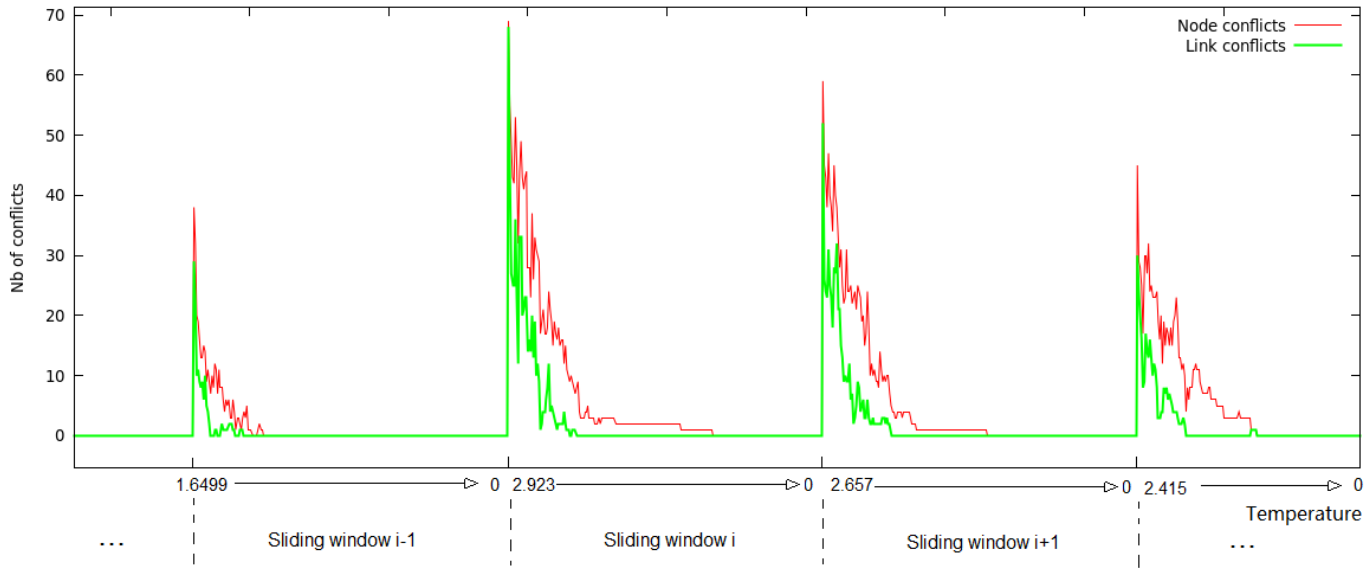


Figure 6. Evolution of conflict value

TABLE VI
USER-DEFINED PARAMETER VALUES

Parameter	Value
Number of iterations at each temperature step	300
Geometrical temperature-reduction coefficient	0.96
Probability of changing the speed	0.25
Probability of changing the time slot	0.25
Probability of changing the landing runway	0.25
Probability of changing the pushback delay	0.25
Airspace weighting coefficient, γ_a	1
Airport weighting coefficient, γ_s	1
Time length of the sliding window, W	3 h
Time shift of the sliding window, S	0.5 h

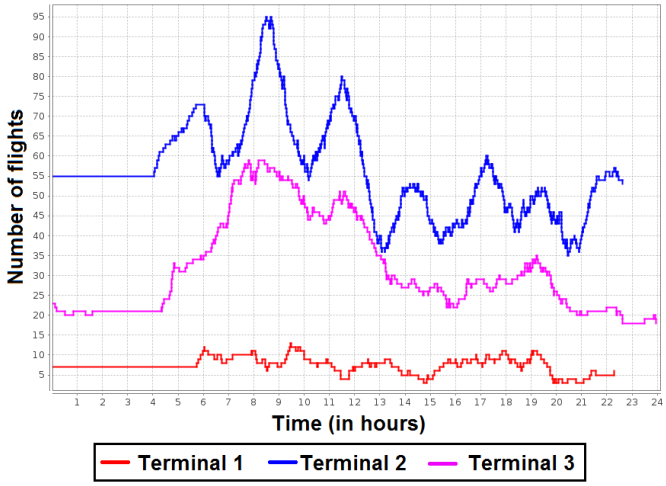


Figure 7. Initial gate occupancy for each terminal

Table VI, the number of conflicts decreases as the temperature decreases, and a conflict-free solution is reached at last for each sliding window. All the other windows have the similar curves and reach conflict-free solutions.

C. Airside evaluation results

1) Terminals: Fig. 7 shows the initial gate occupancy over the course of the day at each of the terminals. We remark that the maximum gate occupancies during the whole day are 13, 95 and 59 for Terminal 1, Terminal 2, and Terminal 3 respectively.

In order to test the performance of our terminal overload mitigation, we set the maximum capacity for the three terminals to be 10, 90 and 56 respectively. We choose these values in a reasonable range to reduce the overload. More tests on the choice of capacity can be done in future work.

The optimization results show an improvement for mitigating congestions in Terminal 2, as illustrated in Fig 8. The maximum gate occupancy is smaller than its capacity limit without any overload compared to the initial situation. This is because the traffic peak in Terminal 2 forms sharp increase and decrease between 8:00 AM and 9:00 AM. The proper adjustment of decision variables can therefore mitigate this peak hour. As our strategy is to delay the arrival aircraft, the curve is shifted to the right compared to the actual occupancy curve.

In Terminal 3 (shown in Fig. 9b), the period of terminal congestion is between 7:00 AM and 10:00 AM, forms a relatively flat curve, it is more difficult to reduce the maximum occupancy below the maximal capacity of the terminal. As for Terminal 1 (shown in Fig. 9a), since the maximum gate occupancy is no more than 13, We did not have sufficiently degrees of freedom to reduce the overload to satisfy the

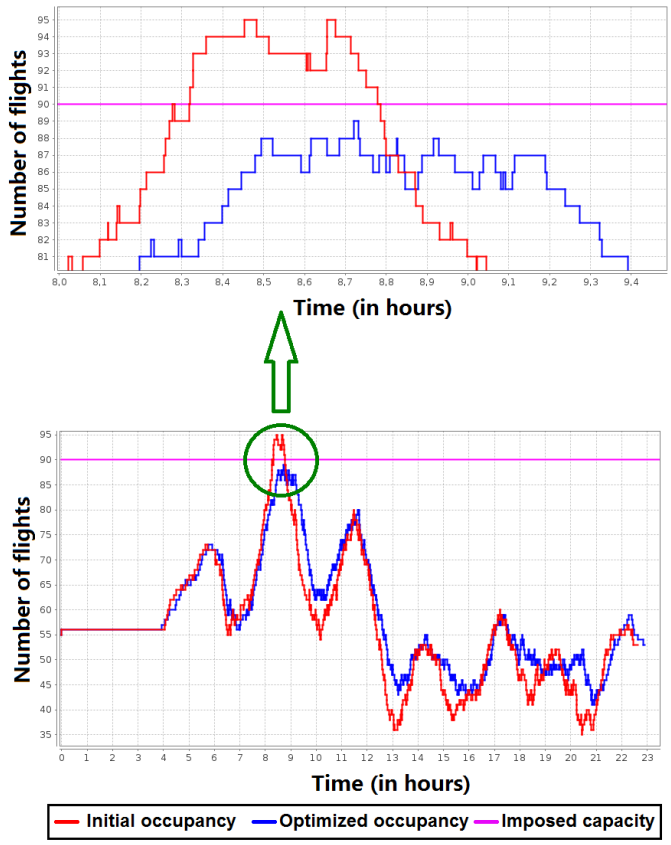
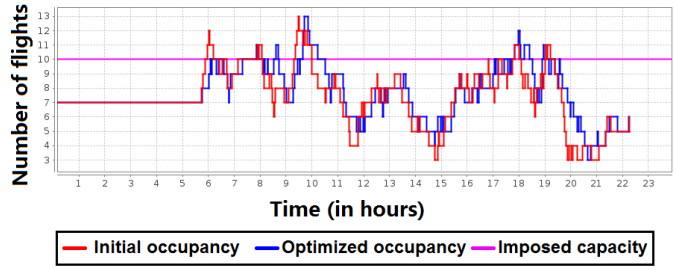
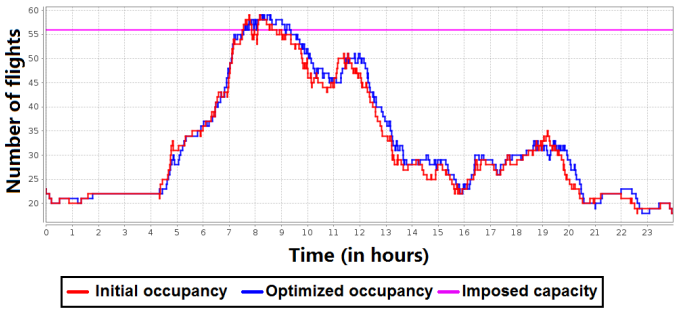


Figure 8. Comparison between initial gate occupancy and optimized one for terminal 2



(a) Terminal 1



(b) Terminal 3

Figure 9. Comparison between initial gate occupancy and optimized one for terminal 1 and 3

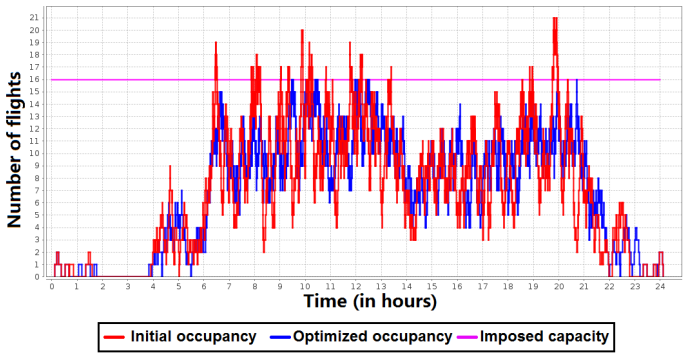


Figure 10. Comparison between initial taxi network occupancy and optimized one

capacity we imposed.

2) Taxi network: In Fig. 10, red curve shows the initial taxi network occupancy during the whole day. We can see that most of the time taxi network occupancy is less than 16, therefore we choose this value as our maximum taxi network capacity to test the performance. More investigations can be done in order to find a proper capacity limit value in future. After optimization, the overload of peak moment between 19:00 PM and 20:00 PM is reduced and the capacity requirement is attained during the whole day.

3) Runway evaluation: After optimization, the separation requirements of the four runways are respected, no violation occurred. This paper is a preliminary study, in future work, the impact of landing runway reassignment in order to balance the capacity need to be investigated. Moreover, we need to consider the runway scheduling in order to minimize the completion time of the flight sequence as well. But these cases are beyond the scope of this paper.

In conclusion, for the one-day real data test, we reached a conflict-free solution in the airspace, and the airside overload is reduced compared to our capacity set. In the future, more high demand traffic scenarios need to be created and to be tested with the real terminal capacities in one airport.

V. Conclusion

To address the tightly connected airport and terminal airspace management problem, this paper proposed a model to manage the arrival, surface and departure problems at a macroscopic level. The objective was to resolve conflicts in the airspace and to reduce airside capacity overload. First, we proposed a TMA route network structure and a low level airport components abstraction model. Then, a time sliding-window approach combined with simulated annealing algorithm is applied to solve the problem. The approach is implemented in real-world traffic case, reaching conflict-free solutions and mitigating the terminal overload by time-slot and speed change.

The next steps for this research would include a more precise microscopic level to optimize the ground movements by considering individual flights and gates. More high traffic demand scenarios need to be created for evaluation.

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REFERENCES

[1] J. E. Beasley, M. Krishnamoorthy, Y. M. Sharaiha, and D. Abramson, "Scheduling aircraft landings - The static case," *Transportation Science*, vol. 34, no. 2, pp. 180–197, 2000.

[2] H. Balakrishnan and B. Chandran, "Scheduling aircraft landings under constrained position shifting," in *AIAA Guidance, Navigation, and Control Conference and Exhibit, Keystone, CO*, 2006.

[3] D. Böhme, "Tactical departure management with the Eurocontrol/DLR DMAN," in *6th USA/Europe Air Traffic Management Research and Development Seminar, Baltimore, MD*, 2005.

[4] H. Balakrishnan and B. Chandran, "Efficient and equitable departure scheduling in real-time: new approaches to old problems," in *7th USA-Europe Air Traffic Management Research and Development Seminar*, 2007, pp. 02–05.

[5] S. Rathinam, J. Montoya, and Y. Jung, "An optimization model for reducing aircraft taxi times at the Dallas Fort Worth International Airport," in *26th International Congress of the Aeronautical Sciences (ICAS)*, 2008, pp. 14–19.

[6] J. Smeltink and M. Soomer, "An optimisation model for airport taxi scheduling," in *Thirtieth Conference on the Mathematics of Operations Research, Lunteren, The Netherlands*, 2005.

[7] P. Roling and H. Visser, "Optimal airport surface traffic planning using mixed-integer linear programming," *International Journal of Aerospace Engineering*, vol. 2008, no. 1, p. 1, 2008.

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

[9] H. Lee and H. Balakrishnan, "A comparison of two optimization approaches for airport taxiway and runway scheduling," in *2012 IEEE/AIAA 31st Digital Avionics Systems Conference (DASC)*. IEEE, 2012, pp. 4E1–1.

[10] R. Deau, J.-B. Gotteland, and N. Durand, "Airport surface management and runways scheduling," in *ATM 2009, 8th USA/Europe Air Traffic Management Research and Development Seminar*, 2009.

[11] H. Khadilkar and H. Balakrishnan, "Integrated control of airport and terminal airspace operations," *IEEE Transactions on Control Systems Technology*, vol. 24, no. 1, pp. 216–225, 2016.

[12] J. Ma, D. Delahaye, M. Sbihi, and M. Mongeau, "Merging flows in terminal maneuvering area using time decomposition approach," in *7th International Conference on Research in Air Transportation (ICRAT 2016)*, 2016.

[13] M. J. Frankovich, "Air traffic flow management at airports: A unified optimization approach," Ph.D. dissertation, Massachusetts Institute of Technology, 2012.