Airport surface management and runways scheduling

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Abstract—This article focuses on the interactions that have to be developed between the runways scheduling (AMAN-DMAN) systems and the surface management (SMAN) system, in order to reduce the ground delay at Roissy Charles de Gaulle airport. The departures delay resulting from the optimised runways scheduling is compared to the total ground delay that can be measured by simulation, when all the taxiing constraints of aircraft are introduced. During traffic peaks, the runways capacity appears to be twice less penalizing than the whole airport traffic management process. As a consequence, some optimisation methods are defined and tested to perform the conflicts resolution between taxiing aircraft and make it more consistent with the runways scheduling. The new ground traffic simulations carried out confirm the significant delay reduction that could be obtained.

Keywords-airport; ground delay; conflicts resolution

I. INTRODUCTION

Air traffic growth was confirmed over the past few years and will certainly continue in the next years: in the european SESAR (Single European Sky ATM Research) project, a very ambitious capacity increase is expected for all of the future ATM systems.

Regarding busy airports, new technologies are available in order to improve the whole ground traffic management process (A-SMGCS: Advanced Surface Movement Guidance and Control Systems). They should moreover allow a better coordination between airport controllers and the approach sectors.

In accordance with these evolutions, this article studies how it could be possible to integrate these future systems together in order to optimise the runways sequences in busy airports while taking into account the complete taxiing constraints of each planned aircraft.

A. Framework

Optimising the trajectories of taxiing aircraft becomes a very complex problem when the number of aircraft increases and when various possible paths are available for each of them: this study concerns the ground traffic management on big international plateforms and will more precisely be applied to Roissy Charles De Gaulle airport.

On such an airport, some big efforts are now invested on the surface management process (SMAN), aiming at decreasing the taxiing times of aircraft with various procedural methods [1], [2], [3]. This problem is actually more complex, especially when it is put in relation with the various other studied concepts: the arrival management (AMAN) and the departure management (DMAN), which have been too often developed separately. Most difficulties actually arise when the constraints of each management process are both considered: the coordination between SMAN and DMAN is notably identified as a very difficult challenge.

From the airport controller's point of view, arriving aircraft are considered to be the entries of the situations to manage, as far as the AMAN systems operate upstream (in the approach sectors) to sequence properly the arrival flow. However, the resulting constraints on the ground traffic management should be well anticipated to manage correctly the departures flow, especially when mixed runways (shared by both departures and arrivals) are in use.

Another kind of constraints more specific to european airports must be taken into account: the take-off slots assigned by the Central Flow Management Unit (CFMU) to some particular departures. Airport controllers are in charge of their application, even if (and especially when) the airport traffic demand is

high.

B. Known difficulties

As introduced before, the interaction between the SMAN systems and the AMAN-DMAN systems appears to be the main difficulty: the current DMAN systems do not integrate the circulation constraints of the aircraft precisely enough and thus can suggest some departures sequences ignoring the delay that can be generated around gates or taxiways intersections. Even if this kind of delay can seem low compared to those resulting from the runways separations, the intended runways sequences however become unmanageable very frequently.

Moreover, SMAN and DMAN systems do not need the same anticipation time, which makes their coordination difficult: at the SMAN level, the distances between aircraft are reduced and aircraft speeds are not well known, so that the system needs a lot of reactivity to keep aircraft separated and can hardly anticipate the traffic situations more than 5 or 10 minutes in advance [4], [5]. Conversely, the AMAN or DMAN systems deal with some higher time separations between aircraft (over one minute) and their targeted anticipation time is consequently around 30 minutes. The synchronisation between data coming from the SMAN and DMAN systems is therefore a complex problem by itself.

C. Goals

This article follows an older publication [4], in which the complexity of the realisation of some optimal runways sequences at the SMAN level was first measured. Two new keypoints are studied here:

- The first section (II) is dedicated to the evaluation of the delay that would affect the departures if the only separations to apply were the ones relative to the runways (thus, ignoring any other kind of ground traffic conflict), and comparing the resulting delay with two different sequencing strategies (optimised or not).
- The next sections (III, IV) try to refine some existing ground conflicts resolution methods in order to fit as better as possible with some targeted optimised runways sequences, in spite of the delay due to the ground conflicts.

II. RUNWAYS SEQUENCES ANALYSIS

This section introduces the runways sequences optimisation problem and defines a deterministic method to solve it, in order to evaluate the minimal ground delay that could be expected at the airport if the runways capacities where the only limiting factor to consider.

A. Principles

The runways sequencing process can be represented easily as a classical constraint satisfaction and optimisation problem:

- The variables of the problem are the take-off or landing slots that must be assigned to the aircraft.
- The main constraints are the runway separation rules, which can be globally described by the miminal separation time required between two aircraft (one, two or three minutes), depending on their wake turbulence categories (low, medium or high). The other constraints are the earliest possible runways access times of each aircraft (the planned landing time for an arrival and the planned off block time added to the minimal taxiing time for a departure).
- The optimisation criterion can be relative to different performance measurement, as the delay generated by the runway sequence and the deviations between the assigned slots and the CFMU required slots for the regulated departures.

Even if this kind of scheduling problem is well known in the litterature, it is combinatorial with the number of aircraft and cannot be solved directly by classical methods if we consider the whole daily traffic of an international airport like Roissy Charles de Gaulle (more than 1500 flights). Moreover, the purpose of a DMAN system is not to build such a complete runway sequence but to find the best (local) solution in a real time environment, within a limited anticipation time (less than one hour).

In order to remain consistent with these real time hypotheses, the runways sequences optimisation is studied on successive time periods during the day, with a limited anticipation time T_{RWY}. A branch & bound algorithm [6] is defined to explore the different runways sequences and find the best solutions.

B. Parameters

Two main parameters can affect the efficiency of the proposed runways scheduling:

- The anticipation time T_{RWY}, that will vary from 10 to 60 minutes;
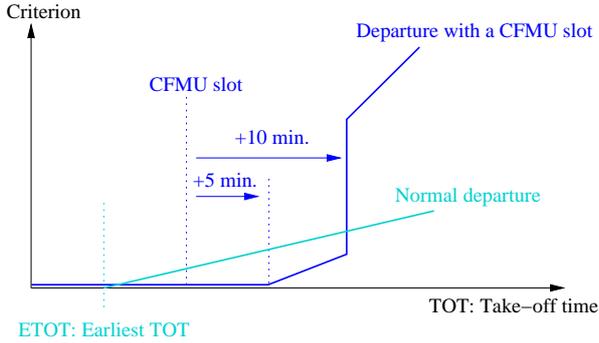
Fig. 1. Minimisation criterion

- The landing times flexibility: the AMAN planned landing times can be lightly modified by airport controllers, as the aircraft can be asked to anticipate or postpone the use of their flaps during the final descent. From the operationnal point of view, this is necessary for the management of the mixed runway but should not exceed $\lambda = \pm 30$ seconds if decided a couple of minutes in advance.

C. Minimisation criterion

The criterion p_i to minimise for an aircraft i is defined as illustrated on figure 1:

- For arrivals, no sequencing penalisation is applied, because the landing times are already constrained by the AMAN scheduling.
- For a regulated departure (which take-off time is constrained by a given CFMU slot), a light penalisation is assigned when the aircraft is scheduled at the end of the CFMU time period acceptance (as this is a very risky scheduling) while a high penalisation is assigned when the aircraft is scheduled after the required slot.
- For other classical departures, the criterion measures the delay resulting from the aircraft scheduled take-off time.

D. The scheduling algorithm

In order to find one of the best solutions, the branch & bound algorithm can potentially explore all the aircraft permutations, but once an acceptable solution is found, the corresponding criterion value is used as an upper bound for the remaining exploration.

Moreover, a lot of permutations can be consistently removed, if it is prooved that they do not lead to a better solution than some other explored permutations:

- At first, swapping two arrivals is obviously not permitted (because the arrivals are considered to be already sequenced by the AMAN system).
- Swapping two *equivalent* departures is useless (as the resulting delay will remain unchanged). The equivalence of two aircraft is relative to their wake turbulence category and their CFMU constraints.
- Some aircraft pairs are *independant* and must not be swapped: this is the case when the earliest runway access time of an aircraft comes far after (more than the required separation time) the initial feasible scheduling of another aircraft.

E. Results

The different optimisation methods are compared by simulating a heavy day of traffic at Roissy Charles de Gaulle airport, in a complex configuration: a mixed runway (on which both arrivals and departures are planned) and two specialised runways (one for the departures and the other for arrivals) are in use and the arriving aircraft have to cross the departures runway after landing.

The optimised runways sequences (OPT) are compared to the first come first served (FCFS) ones and to some older (OLD) ground simulations taking into account all the aircraft ground taxiing constraints [4] with the same traffic sample.

The following table gives the global results of this comparison:

	OLD	FCFS	OPT
Dep. mean delay (sec)	85	54	36
Missed CFMU slots	14	16	14

The first observation concerns the order of magnitude of the delay assigned to departures (that are not regulated), which is much lower than the ones measured by the older simulations (the mean delay is globally reduced more than twice in the optimised scenario). This result allows to quantify the importance of the delay coming from the SMAN constraints compared to the ones coming from the AMAN-DMAN systems: both appear to be more or less equivalent as far as these systems are not sufficiently coordinated.

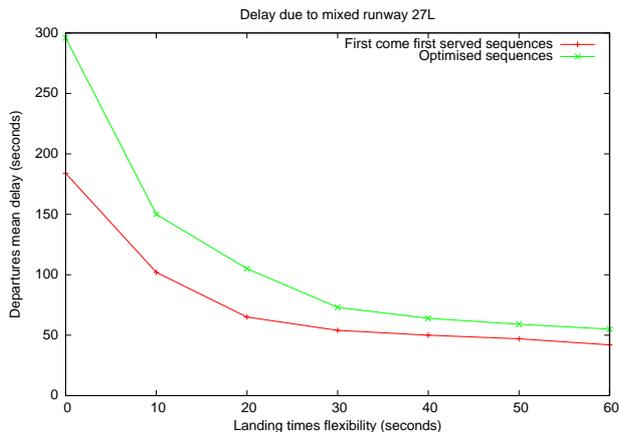Another suprising result is the stability of the mean delay obtained (36 seconds for the optimised

Fig. 2. Influence of the landing times flexibility

Fig. 3. Clusters of conflicting aircraft

runways scheduling) for every different tested values of the anticipation time T_{RWY}. As far as all the SMAN constraints are not involved, the runways sequences could be correctly optimised with an apparently short anticipation time of 10 minutes. However, a higher anticipation time is required for the coordination with approach sectors.

On the contrary, figure 2 shows the good influence of the landing times flexibility on the delay generated by the mixed runway: these figures show that the interaction with the landing times is necessary to manage this particular runway configuration (the delay increases significantly when λ is close to 0). We can also notice that the ± 30 seconds value recomended by the airport controllers appears to be a great compromise between the operational complexity of these interactions and the potential benefits provided to the departures.

III. RUNWAYS SEQUENCES INTEGRATION IN THE SURFACE MANAGEMENT

A. Simulation of the surface management (SMAN)

A more detailed description of the ground traffic simulator used in this study in order to simulate the surface management at Roissy can be found in [7]: this section only summarizes the main ideas that are directly involved in the next sections.

1) General overview: The airport is modeled as a graph of taxiways, linking its gates to its runways (see figure 3). This graph allows to assign to each aircraft a set of various possible paths [8] taking into account the maximal taxiing speeds on each taxiway portion and respecting the exploitation procedures in use (as oneway taxiways for example).
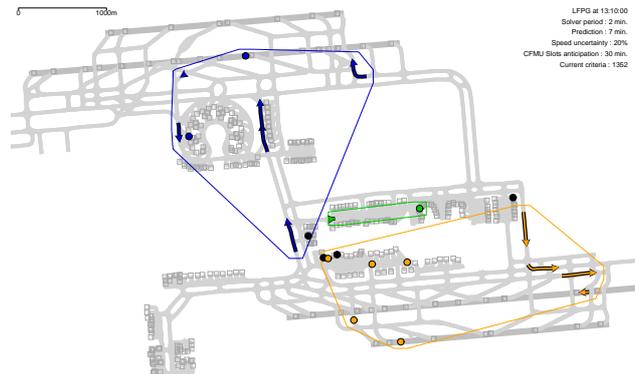
The traffic sample is described by the actual flight-plan data of one day at Roissy airport. Each flight-plan gives all the information needed to reproduce an aircraft evolution and its constraints, including the aircraft type, the gate and runway used, the ready-to-go time for a departure, the landing time for an arrival, etc. For a regulated departure, the flightplan also provides the special take-off slot required by the CFMU.

The traffic simulation of a complete day at Roissy airport is carried out by iterations, using a prediction time window T_w and a resolution period $\Delta < T_w$: at each time t in the simulation (every Δ minutes), a traffic prediction is performed within the time window $[t; t + T_w]$. The possible future positions of each aircraft are computed relatively to a given speed uncertainty, defined as a fixed percentage of the nominal speed: this uncertainty makes aircraft positions become lines of possible positions in the prediction (see figure 3).

2) Aircraft separation rules: Separation rules between active aircraft are modeled as follows:

- Aircraft waiting at the gate position are considered separated from all other aircraft (while any other aircraft attempts to access the gate).
- The distance between two moving aircraft must always be above 60 meters.
- After each take-off or landing, a minimal separation time is required to clear the next move from the wake turbulence.
- When an aircraft is taking off or landing on a given runway, the other aircraft can be crossing this runway area or taxiing in it, as long as they are behind it (in accordance to current controllers practices).
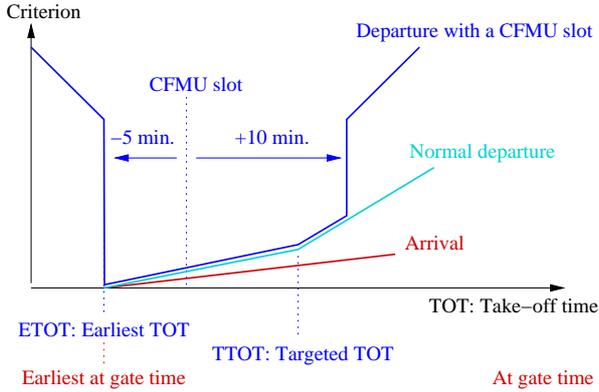
Fig. 4. Criterion to minimize

When two aircraft trajectories does not respect these rules in the prediction, the aircraft pair is *in conflict*. The transitive closure of this relation gives the *clusters* of conflicting aircraft. The conflicts of each cluster can be solved separately as far as the resulting decisions do not create new conflicts between aircraft of different clusters (in which case, the concerned clusters would have to be joined together).

3) Optimisation criterion: The separation rules described in the previous section represent the constraints of the problem to solve in each ground traffic situation. Among all the acceptable solutions, some are better than others in terms of aircraft delay or runways sequences optimisation: the optimisation criterion allows to evaluate each solution in order to compare them and select the best.

For the purpose of this article, the selected optimisation criterion is a function to minimise, defined as the sum of each particular criterion relative to each aircraft: (see figure 4):

- For classical departures (not regulated by the CFMU): the criterion measures the ground delay assigned to the aircraft, and is twice more penalising when the resulting take-off time of the aircraft comes over its targeted runway slot.
- For regulated departures: the criterion measures also the application of the CFMU slot (with respect to the CFMU official acceptance).
- For arrivals: the criterion measures the ground delay assigned to the aircraft with a smaller ponderation, in order to give a higher priority to the departure flights.

4) Conflicts resolution: In order to solve a cluster of conflicting aircraft (i.e. ensure the separations between all the concerned aircraft), some decisions

must be taken by the controllers. In the simulation, these decisions concern:

- The path that each aircraft must follow;
- If needed, one or more positions to hold by some aircraft;
- For the arrivals, the exact landing time can be lightly moved compared to the one forecasted by the AMAN system, as described in II-B.

Thus, the problem is to find the most appropriate control decisions to ensure aircraft separations on the taxiways and in the runways areas, while minimising the global optimisation criterion. Thus formulated, this optimisation problem is obviously combinatorial with the number of aircraft and cannot be solved by exact methods: sections III-D and III-E describe the two different methods used.

B. Runways sequences integration

To be relevant, the runways sequences planned by the departure manager (DMAN) must be taken into account in advance, during all the surface management process and the resolution of each ground traffic situation. Different strategies can be developed to fit as often as possible to these planned sequences:

- A first idea is to solve the ground conflicts by delaying first the departures that are the most ahead of their runway slot in the targeted sequence. This can be quantified by the following measure:

$$\alpha = TOT - R - t$$

where:

  - TOT is the targeted take-off time for the aircraft
  - R its minimal remaining taxiing time
  - t the current time

- Another common principle is to lead the departure aircraft to reach the runway threshold in the right order and at the right moment (not too late but not too early either). For this purpose, a strategic off block time can be computed for each departure: this point is detailed in section III-C.

However, the runways sequences anticipation time ($T_{RWY} \simeq 30$ minutes) is far greater than the ground traffic situations anticipation ($T_w \simeq 5$ minutes) and it seems unavoidable that some of these situations eventually conflict with the initial targeted sequences (especially when some departure times are delayed too much). When such a situation occurs, the latest
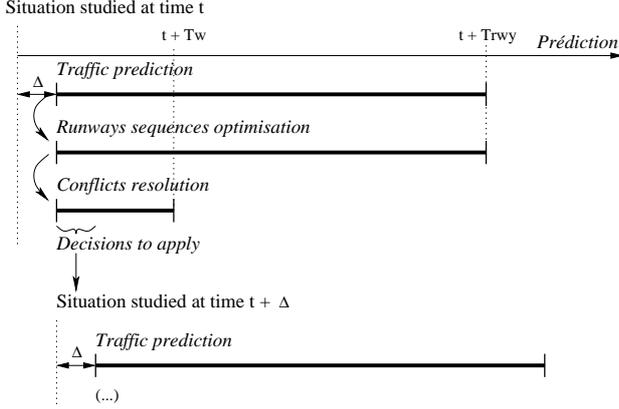
Fig. 5. Runways sequence optimisation and conflicts resolution

position of each aircraft must be taken into account and the runways scheduling must be updated.

As a consequence, the targeted runways sequences must be regularly updated (every Δ minutes) in accordance with the ground traffic situation, before and after each conflict resolution, and the scheduling must be kept as close as possible to the previous one. For these reasons, the airport simulations are carried out with the following iterative process (see figure 5):

1) Predict the traffic at time t, with the DMAN anticipation time, on the period $[t; \ t+T_{RWY}]$;
2) Update the runways scheduling;
3) Solve the conflicts with the SMAN anticipation time, on the period $[t; \ t+T_w]$;
4) Build the new situation applying the SMAN decisions on the period $[t; \ t+\Delta]$ and go on with the next situation:
$t \leftarrow t + \Delta$.

C. Strategic departures off block times

In order to dispatch the departure traffic on the taxiways in accordance with the targeted runways sequences, some strategic off block times can be assigned to the aircraft (asking them to hold at the gate position even if ready). The main idea is to ensure that after leaving the gate, an aircraft cannot preceed another aircraft if its take-off time comes after chronologically. Thus, if a departure i is planned before another departure j in the runway sequence, then the following relation must be verified:

$$OBT_i + t_i \leq OBT_j + t_j$$

where:

- OBT_i is the off-block time of aircraft i
- t_i is the minimal taxiing time of aircaft i

This relation gives a recurrent definition of the strategic off-block times (SOBT) for the departures planned in the same runway sequence (if the aircraft are indexed in respect with the sequence):

$$\begin{cases} SOBT_0 = EOBT_0 \\ SOBT_{i+1} = \max(EOBT_{i+1}, SOBT_i + t_i - t_{i+1}) \end{cases}$$

where $EOBT$ is the earliest possible off-block time for the aircraft.

D. The sequential resolution method

In order to solve the ground conflicts between aircraft, a first sequential method consists in simplifying the described problem by assuming a classification of the concerned aircraft: the first aircraft is considered to have the highest priority and is assigned its shortest path without any holding position. Then, the $(n+1)$th aircraft trajectory is found by solving the conflicts with the n previously optimised and fixed trajectories. A deterministic branch & bound algorithm [9], [6] can easily test if a solution exists for each aircraft, and in such a case, finds the best solution (relatively to the global criterion to minimise) for each of them.

When the considered classification comes to a problem without any solution for an aircraft, the classification can be adapted (by upgrading the priority level of the concerned aircraft) and the process restarted with this new classification. Past simulations [5] have shown that this deterministic method improved with the possible adaptation of the classification could solve correctly all the ground situations at Roissy.

Moreover, this resolution method has the great advantage to be directly compatible with the constraints coming from the DMAN and AMAN systems: the initial classification can be provided by the targeted runways sequences. Thus, the priority levels of aircraft can be defined as follows:

$$Prio_i = Slot_i$$

where $Prio_i$ is the priority level of aircraft i and $Slot_i$ its landing or take-off slot in the targeted runway sequence.

It is also interesting to decrease the priority level of the already landed aircraft in order to favour the

taxiing departure flow (as often recommanded by operationnal controllers):

For a landed aircraft i: $Prio_i = Slot_i - \delta_{ARR}$

For practical purposes, δ_{ARR} is a duration parameter allowing to adjust the priority level of the departure flow and can be experimented with values varying from a few minutes (light penalisation of the arrivals) to one or more dozens of minutes (departures always favored).

E. The genetic algorithms based method

1) Goals: The sequential method described in the last section presents some various disadvantages:

- It deals with a simplification of the global optimisation problem, so that all the possibilities ar not explored and the best solution is hardly obtained.
- It requires a total classification of aircraft. Even if this classification should not be penalising for aircraft sharing the same runway (as they must anyway use the runway one after the other), it can appear unadapted between aircraft of different runways when they are moving near gates and taxiways areas.

To overcome these drawbacks, the conflict resolution problem must be considered in its general formulation and its solutions explored with different types of methods like genetic algorithms, as presented in the litterature [10], [11].

2) Implementation: In this article, the sequential method is compared to an hybrid optimisation method, based on a genetic algorithm exploring the possible combinations of paths and priority levels assignments and using the branch & bound algorithm to develop each solution:

- A chromosome is defined by $2N$ integer variables $\{(n_i,\ p_i)\}_{1 \leq i \leq N}$, where N is the number of aircraft in the cluster to solve, n_i the path assigned to aircraft i and p_i its priority level.
- The evaluation of a chromosome is performed by the branch & bound algorithm used in the sequential method, limited to the paths and the classification described by this chromosome.
- The fitness function f is defined in accordance to the constraints that have to be respected and the global criterion to minimise:

  - For a chromosome with $n_c > 0$ aicraft without any solution:

  $$f = \frac{1}{1 + n_c}\ (< \frac{1}{2})$$

  - For a chromosome corresponding to an acceptable solution:

  $$f = \frac{1}{2} + \frac{1}{2 + \sum_{i=1}^{N} p_i}\ (> \frac{1}{2})$$

  where p_i is the criterion to minimise for aircraft i, as described in section III-A3.

With this definition, the fitness function is partially separable as defined in [12] and can be associated with some improved crossover and mutation operators to speed up and improve the genetic algorithm convergence.

IV. RESULTS

A. Simulations

The different optimisation methods are compared by simulation, using the same traffic sample (and the same runways configuration) than in section II.

The anticipation time of the AMAN-DMAN process is set to 30 minutes (for the runways sequences optimisation) while the SMAN anticipation time (for the ground conflicts resolution) is set to 5 minutes.

Three scenarios are compared:

- One using the sequential resolution method with a basic runways sequencing process (first come first served);
- The second one using the same sequential method but with the optimised runways sequencing process, as described in section III-D;
- The last one concerns the hybrid genetic algorithm associated with the optimised runways sequencing, as described in section III-E.

B. Departures delay

Figure 6 shows the variations of the delay assigned to the classical departures during the day, in the three studied scenarios. The delay generated by the three traffic peaks (around 10am, 2pm and 7pm) can be quantified. We can notice the significant delay reduction due to the optimisation on the runways sequences (between one and two minutes per aircraft are saved during these traffic peaks).

We can also observe the improvment provided by the hybrid genetic algorithm compared to the sequential resolution method.
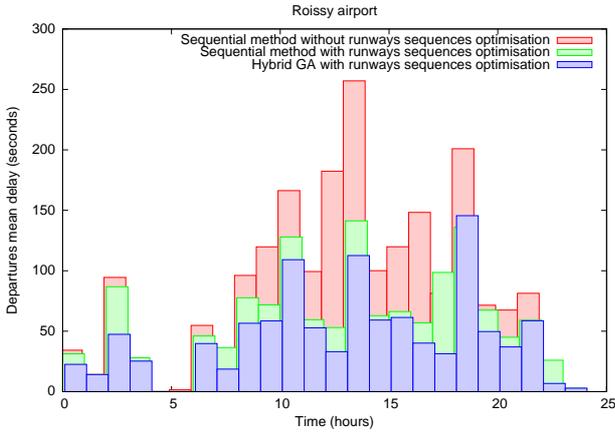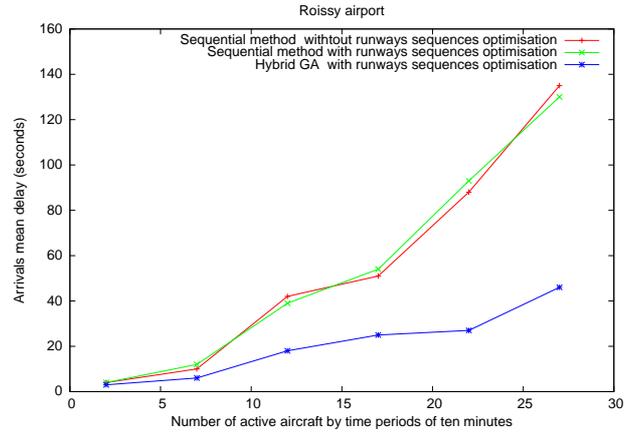
Fig. 6. Departures delay during the day

Fig. 8. Arrivals delay as a function of the number or aircraft
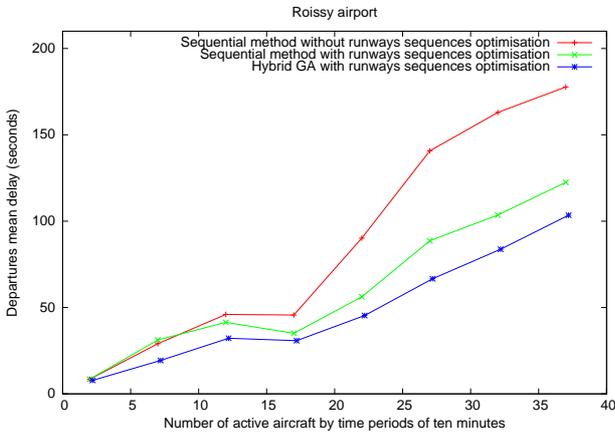

Fig. 7. Departures delay as a function of the number of aircraft

Figure 7 shows the departures mean delay as a function of the number of moving aircraft by time periods of 10 minutes and confirms the efficiency of the runways sequences optimisation process, especially during traffic peaks.

C. Arrivals delay

Figure 8 enlightens the most important difference between the two compared resolution methods: the ground delay assigned to the arriving aircraft (after landing) is reduced from 140 seconds down to 40 seconds during the traffic peaks with the genetic algorithms method. This result shows up the lack of flexibility of the aircraft classification made in the sequential method, in which a higher priority level has to be given to the departures in order to apply correctly the targeted runways sequences.

V. Conclusions

The runways sequences analysis carried out in section II evaluates the ground delay that would result from the only runways capacities limits at Roissy Charles de Gaulle airport: this delay appears to be half less important than the delay measured by a complete ground simulation of the same traffic sample, in which the whole taxiing constraints of aircraft are considered (even if some efficient optimisation methods are used to solve the ground conflicts between aircraft). These results show all the complexity of the surface management process on such a busy airport and enlightens the challenge that must be performed in the next years concerning the conception of some well coordinated AMAN-DMAN and SMAN systems.

In the following sections, the ground conflicts resolution algorithms are refined. These kind of algorithms could be integrated in the SMAN system of the airport, in order to minimise the impact of the taxi delay and to fit to an evolutive runways scheduling: the use of a more global optimisation method, associated with the definition of some strategic off-block times for departures allows to reduce significantly the ground delay, despite of the considered aircraft speed uncertainties and the well known gates and taxiways congestion areas.

This way, the SMAN system should take a great advantage of its synchronisation with the AMAN-DMAN systems: the efficiency of a basic sequential resolution method is largely enhanced when the needed aircraft classification is deduced from the optimal runways scheduling. Obviously, keeping in mind this scheduling allows to select some more

consistent solutions for the ground traffic situations, especially when the concerned aircraft are far from the runways. The resulting ground delay should be reduced and the traffic predictions of the DMAN system should become more relevant.

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