Coordination of scheduling decisions in the management of airport airspace and taxiway operations

M. Samà, A. D’Ariano, F. Corman, D. Pacciarelli
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- Introduction
- Modeling a terminal control area
- Aircraft scheduling policies
- Mathematical formulations
- Solution methods
- Experiments
- Conclusions

dariano@ing.uniroma3.it
Air Traffic Control (ATC)

An efficient control of air traffic must ensure **safe, ordered and rapid** transit of aircraft on the ground and in the air resources.

With the increase in air traffic [*], aviation authorities are seeking methods (i) to *better use* the existing airport infrastructure, and (ii) to *better manage* aircraft movements in the vicinity of airports during operations.

[*] Source: IATA 2014
Status of the current ATC practice

Airport resources are becoming a major bottleneck in ATC operations.

• ATC operations are still mainly performed by human controllers whose computer support is most often limited to a graphical representation of the current aircraft position and speed.

• Intelligent decision support is under investigation in order to reduce the controller workload (see e.g. recent ATM Seminars).
Literature: Aircraft Scheduling Problem (ASP)

Terminal Control Area (TCA)

Airport Traffic Control Towers
Approach Control
En-route Control
Terminal Control Area (TCA)
Approach Control
Airport Traffic Control Towers

Existing Approaches
Basic Detailed
Static Dynamic

Chris Potts et al. 4OR 2011
Our approach for TCAs

In this paper we investigate:
Our approach for TCAs

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- Aircraft scheduling policies: wait-at-gate versus free-the-gate, wait-on-route versus free-the-route
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• Detailed ASP-TCA models: incorporating safety rules at air segments, runways and taxi segments
Our approach for TCAs

In this paper we investigate:

• Aircraft scheduling policies: 
  *wait-at-gate versus free-the-gate, wait-on-route versus free-the-route*

• Detailed ASP-TCA models: 
  *incorporating safety rules at air segments, runways and taxi segments*

• Alternative objective functions & solutions methods: 
  *minimization of Maximum Delay (min MD), Average Delay (min AD), average Approach Time (min AT), average Taxi Time (min TT)*
Our approach for TCAs

In this paper we investigate:

- Aircraft scheduling policies: wait-at-gate versus free-the-gate, wait-on-route versus free-the-route

- Detailed ASP-TCA models: incorporating safety rules at air segments, runways and taxi segments

- Alternative objective functions & solutions methods: minimization of Maximum Delay (min MD), Average Delay (min AD), average Approach Time (min AT), average Taxi Time (min TT)

- Real-world instances of Amsterdam Schiphol Airport: coordination of ground and air operations in case of disturbed traffic
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Schiphol airport, Amsterdam, The Netherlands
Schiphol airport
Schiphol airport

AIR SEGMENTS
Schiphol airport

AIR SEGMENTS

COMMON GLIDE PATH
Schiphol airport

AIR SEGMENTS

RUNWAYS

RUNWAYS FOR LANDING OPERATIONS

RUNWAYS FOR TAKE-OFF OPERATIONS
Schiphol airport

AIR SEGMENTS

RUNWAYS

TAXI SEGMENTS
Schiphol airport

AIR SEGMENTS

RUNWAYS

TAXI SEGMENTS
Schiphol airport

- AIR SEGMENTS
- RUNWAYS
- TAXI SEGMENTS
- GATE AREAS
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Scheduling policies for take-off aircraft

**wait-at-gate:**
Each aircraft leaves the gate when it can reach the runway without waiting on the taxiway.
Scheduling policies for take-off aircraft

**wait-at-gate:**
Each aircraft leaves the gate when it can reach the runway without waiting on the taxiway.

**free-the-gate:**
Each aircraft leaves the gate as soon as possible, possibly queueing on the taxiway before using the runway.
Scheduling policies for take-off aircraft

**wait-at-gate:**
Each aircraft leaves the gate when it can reach the runway without waiting on the taxiway.

**free-the-gate:**
Each aircraft leaves the gate as soon as possible, possibly queueing on the taxiway before using the runway.
Scheduling policies for landing aircraft

wait-on-route:
Each aircraft enters the TCA only when it can land and reach the gate without further delay.
Scheduling policies for landing aircraft

**Free the route**

**wait-on-route:**
Each aircraft enters the TCA only when it can land and reach the gate without further delay.

**free-the-route:**
Each aircraft enters the TCA as soon as possible, then the traffic controllers can use time reserves to move the aircraft to the gate.
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**ASP Model: Alternative Graph (AG)**

[Masci & Pacciarelli EJOR 2002]

**Release time** $\alpha_A = \text{expected entry time of aircraft A}$

**Fixed constraint**: $t_{A11} = t_0 + \alpha_A$
AG Model

Entry due date \( \beta_A = -\alpha_A \)

Fixed constraint : \( t_n = t_{A11} + \beta_A \)

Example : \( t_{A11} = 8:05 \text{ PM} ; \alpha_A = 8:00 \text{ PM} \rightarrow t_n = 5 \text{ minutes} \)
AG Model

Wait-on-route policy for landing aircraft A only if
\[ w_{A11 A13} = - w_{A13 A11} ; w_{A13 A21} = - w_{A21 A13} ; \ldots ; w_{A36 AG41} = - w_{AG41 A36} \]

Exit due date \( \gamma_A = - \) expected arrival time of aircraft A at G41
AG Model

Free-the-route policy for landing aircraft A

The traversing time of the air segments is constrained in a time window of minimum \( w_{A11 \to A13} \) and maximum \( -w_{A13 \to A11} \) times
Wait-at-gate policy for take-off aircraft B only if
\[ W_{BG42\ B37} = - W_{B37\ BG42} ; \cdots ; W_{B23\ Bout} = - W_{Bout\ B23} \]
AG Model

Free-the-gate policy for take-off aircraft B
**AG Model**

*Wait-on-route* for A and C

*Wait-at-gate* for B
AG Model

Aircraft sequencing problem
between A and C on:
• air segment 13
AG Model

Aircraft sequencing problem
between A and C on:
• air segment 13
• taxi segment 36
AG Model

Aircraft sequencing problem
between A and C on:
• air segment 13
• taxi segment 36
• crossing point 34
AG Model

Aircraft sequencing problem between A, B and C required on crossing point 34
AG Model

Aircraft sequencing solution:
C → A on air segment 13
C → A on taxi segment 36
C → A → B on crossing point 34
AG viewed as a Mixed-Integer Linear Program

\[
\min f(t, x)
\]

\[
t_{Bi} \geq t_{Ah} + w_{Ah,Bi} \quad \forall (Ah, Bi) \in F
\]

\[
t_{Bi} \geq t_{Ah} + w_{Ah,Bi} - Mx_{AhBiBkAj} \quad \forall [(Ah, Bi), (Bk, Aj)] \in A
\]

\[
t_{Aj} \geq t_{Bk} + w_{Bk,Aj} - M(1 - x_{AhBiBkAj}) \quad \forall [(Ah, Bi), (Bk, Aj)] \in A
\]

\[
x_{AhBiBkAj} \in \{0, 1\} \text{ for each pair } [(Ah, Bi), (Bk, Aj)] \in A
\]

- **Fixed constraints** in \( F \) model a feasible timing for each aircraft for a given policy, plus \( \alpha, \beta, \gamma \) constraints on the entrance and exit times.
- **Alternative constraints** in \( A \) model the aircraft sequencing decisions at air segments, taxi segments (including crossing points) and runways.

[Samà et al. TRpartE 2013, TRpartC 2014, Omega 2017]
Objective functions

minimization of Maximum Delay (min MD)

\[ \text{min } t_n \]
Objective functions

minimization of
Average Delay (min AD)

\[
\min t_{A11} + \beta_A + t_{AG41} + \gamma_A + t_{C12} + \beta_C + t_{CG42} + \gamma_C + t_{Bout} + \gamma_B
\]
Objective functions

minimization of avg Approach Time (min AT)

\[ \min t_{A21} - \alpha_A + t_{C22} - \alpha_C \]
Objective functions

minimization of avg Taxi Time (min TT)

\[
\min t_{AG41} - t_{A21} + t_{CG42} - t_{C22} + t_{Bout} - t_{BG42}
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Optimization Framework & Algorithms

- Exact method developed in the IBM-ILOG-CPLEX solver;
- Fast heuristics developed in the ROMATRE-AGLIBRARY solver;
- H1 Heuristic: FCFS on the runways + B&B* method on the other resources;
- H2 Heuristic: FCFS on the runways + Arc Greedy* on the other resources;

[* D’Ariano et al. Networks 2015; Samà et al. Transportation Res. Part C 2017]
On the ROMATRE-AGLIBRARY algorithms

☐ Arc Greedy 1: AMCC (Avoid Most Critical Completion time)
Choices the alternative pair containing the arc which would cause the largest increase of the aircraft maximum delay.

☐ Arc Greedy 2: AMSP (Avoid Max Sum Pair)
Chooses the alternative pair with the largest sum of aircraft delays.

☐ B&B branching rule: Choose the most critical unselected alternative pair with criteria AMSP and branch on this pair.

☐ B&B search strategy: Alternate four repetitions of the depth-first visit with the choice of the open node of the search tree with the smallest lower bound among the last five generated nodes.

[* D’Ariano et al. Networks 2015; Samà et al. Transportation Res. Part C 2017]
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Amsterdam Schiphol instances

| Landing Aircraft | Take-off Aircraft | $|N|$ | Min $|F|$ | Max $|F|$ | $|A|$ |
|------------------|-------------------|------|---------|---------|------|
| 35               | 35                | 652  | 1001    | 1266    | 9448 |

- 70 aircraft partitioned into four different size categories (heavy, medium, small and light), with different characteristics of separation times;
Amsterdam Schiphol instances

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- Infrastructure used for the Amsterdam Schiphol airport: 7 gates areas, 18 air segments, 4 runways, 14 ground segments and 2 crossing points.
## Amsterdam Schiphol instances

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- Aircraft entrance delays are randomly generated with Weibull probability distributions. Arrivals positive [negative] deviation is 653 [-1315] sec. Departures positive [negative] deviation is 549 [-216] sec.
## Single-indicator optimal solutions

ASP solutions are computed by means of IBM CPLEX MIP solver 12.0.

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<tr>
<th>MILP Formulation</th>
<th>MD (sec)</th>
<th>AD (sec)</th>
<th>AT (sec)</th>
<th>TT (sec)</th>
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## Pareto optimal solutions

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## Pareto optimal solutions

ASP solutions are computed by means of IBM CPLEX MIP solver 12.0.

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<th>AT (sec)</th>
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Solutions computed by the heuristics

- ASP solutions are computed by means of RomaTre AGLIBRARY solver.

Heuristic H1 (FCFS on the runways + B&B method)

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Heuristic H2 (FCFS on the runways + Best Arc Greedy)

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Optimal values for each performance indicator:
Min MD = 170 sec; Min AD = 8 sec; Min AT = 1172 sec; Min TT = 1069 sec.
Coordination of scheduling decisions in the management of airport airspace and taxiway operations

- Introduction
- Modeling a terminal control area
- Aircraft scheduling policies
- Mathematical formulations
- Solution methods
- Experiments
- Conclusions

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Achievements

• Detailed ASP-TCA models and methods are proposed to improve the coordination of aircraft scheduling decisions at a busy airport.

• Various indicators and policies are incorporated and investigated.

• Computational results for the main Dutch TCA demonstrate the existence of relevant gaps when optimizing different indicators.

• The “free” scheduling policies can be used for better reducing aircraft delays, require less TCA/en-route coordination, and help to increase airport throughput.


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On-going and future research directions

- Development of **exact aircraft scheduling and routing approaches** and their assessment under disturbed traffic conditions (e.g. wind)
- **Multi-criteria optimization** for aircraft management at busy TCAs (e.g. including robustness, priority classes, environmental factors)
- **Optimization of aircraft trajectories** in the vicinity of TCAs
- **Rolling horizon approaches** for dealing with real-time uncertainties

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