Management of Time-Based Taxi Trajectories
Coupling Departure and Surface Management

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### Motivation


“First Come, First Served” at departure runways reduces the efficiency of a DMAN [Eurocontrol Workshop 2009].

Holding departures at the parking positions can decrease fuel consumption by up to 24 % [Griffin et.al. / Simaiakis et al.]

First Surface Management Systems are on their way.

Today time based trajectories start with departure and end with arrival => Extend these trajectories to ground.

### Conclusion

Combine DMAN and SMAN for a punctual arrival at the departure runway together with an optimized departure sequence taking all available departures into account.
Motivation – 4D-Trajectories => SMAN

“An ATM tool that determines optimal surface movement plans (such as taxi route plans) involving the calculation and sequencing of movement events and optimizing of resource usage (e.g. de-icing facilities).“

Source: EUROCONTROL ATM Lexicon
## Vision of an SMAN

Create a conflict-free, optimized 4D-trajectory for every aircraft on ground including taxi and runway crossing clearances.

Meet specified target times like runway crossing and target take-off times.

Monitor these trajectories for spatial and time deviations.

Adapt planned trajectories to reality.

Carry out conflict detection and resolution.

Create new trajectories when target times are violated or conflicts are detected.

Inform departure management systems about changed arrival times at departure runway.

## Future Tasks

Improving performance by providing more reliable arrival times at departure runways for DMAN.

Increase safety by detecting conflicts in advance.
CADEO: Controller Assistance for Departure Optimization

- Prototype of a departure management system of DLR.
- Implementation of the concept of departure runway sequence optimization.
- Optimization Objectives: Throughput enhancement, slot compliance, plan stability, taxi-out delay reduction.
TRACC: Taxi Routing for Aircraft: Creation and Controlling

- Prototype of a surface management system (SMAN) of DLR.
- Create, control and always maintain conflict-free and times-based trajectories:
  
  Plan ➔ Execute ➔ Measure ➔ Adapt  [Eurocontrol]

- Speed and taxi advisories for ATCOs.

Departure Management System CADEO

Surface Management System TRACC
TRACC: Taxi Routing for Aircraft: Creation and Controlling

<table>
<thead>
<tr>
<th>Technical Pre-Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datalink</td>
</tr>
<tr>
<td>Ability of pilots to follow speed advisories (support tool e.g. integrated in flightdeck)</td>
</tr>
<tr>
<td>Position of aircraft always known</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic tool (no assumptions for specific airports)</td>
</tr>
<tr>
<td>Node-link model as backbone with different link types (runway, taxiway, apron…)</td>
</tr>
<tr>
<td>Taxi speed range for every link type</td>
</tr>
<tr>
<td>Conformance monitoring for all aircraft</td>
</tr>
<tr>
<td>Conflict detection and resolution for each time step</td>
</tr>
<tr>
<td>Trajectories from runway exit to position and from position to runway holding point</td>
</tr>
</tbody>
</table>
TRACC – CADEO Coupling

**CADEO Responsibility**
- Calculation of departure sequence
- Calculation of target line-up times

**TRACC Responsibility**
- Calculation of conflict-free trajectory
- Calculation of RLUT as basis for earliest possible departure time
- Calculation of start-up time (TSAT) for decreasing the taxi time
- Update earliest and estimated arrival time at runway holding point every time a deviation takes place
TRACC-CADEO Coupling}

Trajectory Planning and Optimization

TSAT

ELUT

TLUT

TTOT

TOBT

Initial Trajectory

ELUT: Estimated Lineup Time
RLUT: Earliest Lineup Time
TLUT: Target Lineup Time
TOBT: Target Off-Block Time
TSAT: Target Startup Time
TTOT: Target Takeoff Time
**Pushback Management**

**Workflow**

- **First Optimization:**
  
  - **TSAT := TOBT := CSAT**

- **Calculate TOBT Delay**
  
  - If TOBT-Delay > 0, set CSAT and TSAT:
    
    \[
    CSAT = \max\{CSAT, TOBT + TOBT-Delay\} \\
    TSAT = \max\{TOBT + TOBT-Delay, TSAT\}
    \]

- **Set CSAT and TSAT**
  
  - If CSAT > TSAT, set TSAT = CSAT; otherwise, set TSAT = TOBT

- **Calculate TSAT Starting from CSAT**

- **Conflicts Check TOBT**
  
  - If conflict, TOBT-Delay = 0

- **Set earliest conflict-free TSAT**

- **Conflicts Check TSAT**
  
  - If conflict, earliest conflict-free TSAT

- **Take pushback conflicts into account => TOBT-Delay**

- **Take possible gridlocks on single lane taxiways into account => CSAT**

- **Calculate intermediate TSAT respecting given TSAT and CSAT**

- **Check intermediate TSAT for pushback problems**

**Legend**

- TLUT = Target Line-Up Time
- TOBT = Target Off-Block Time
- TSAT = Target Start-Up Time
- CSAT = Calculated Start-Up Time
**Workflow**

Start with $\text{TSAT} = \text{TOBT}$.

Recalculate $\text{TSAT}$ using Push-Back-Management.

Calculate estimated line up time ($\text{ELUT}$) with this $\text{TSAT}$.

Compare $\text{ELUT}$ with target line-up time ($\text{TLUT}$)

Adapt $\text{TSAT}$ to $\text{TLUT}$ if necessary (not conflict free!)

Recalculate $\text{TSAT}$ using Push-Back-Management.

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**TSAT-Management**

1. $\text{TSAT} := \text{TOBT}$
2. Push-Back-Management $\Rightarrow \text{TSAT}2$
3. $\text{ELUT} = \text{TSAT}2 + \text{VTT}$
4. $|\text{TimeGap}| = \text{TLUT} - \text{ELUT}$
5. Yes, $\text{TimeGap} < 0$:
   - $\text{TSAT}3 = \max(\text{TSAT}2 + \text{TimeGap}, \text{CSAT})$
6. No:
   - $\text{TSAT}3 = \text{TSAT}2$
7. Yes, $\text{TimeGap} > 0$:
   - $\text{TSAT}3 = \text{TSAT}2 + \text{TimeGap}$
8. Push-Back-Management $\Rightarrow \text{TSAT}4$
9. Conflict-free $\text{TSAT}$
RLUT Calculation

**Requirements**

- Pushback and TSAT Management must be carried out before RLUT Calculation.
- First conflict free trajectory must be calculated.

**Two Step Approach**

- Increasing speeds of the optimized trajectory by a certain amount and check for conflicts.
  - No conflicts: Use the resulting estimated line-up time as RLUT.
  - Conflicts: Handover of trajectory to optimization algorithm and calculate new trajectory with optimization parameter “Shortest Taxi Time”. Use the resulting estimated line-up time as RLUT.

- Send new RLUT to CADEO.

- Process is carried out each time a new trajectory is created.
## Importace of CD&R

<table>
<thead>
<tr>
<th>Backbone of coupling DMAN and SMAN if a supervising of aircraft takes place.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty is the main reason for reduced benefit when using a departure management system [Gupta / Jung 2010].</td>
</tr>
<tr>
<td>Reducing uncertainty means using supervised 4D trajectories with adaptions and recalculations if necessary.</td>
</tr>
<tr>
<td>Up to date information (R/ELUT) for DMAN.</td>
</tr>
<tr>
<td>-&gt; New target times for SMAN</td>
</tr>
</tbody>
</table>
Conflict Detection and Resolution

Maintain Conflict-Free Trajectories by

1. Identification of deviations from planned trajectory

2. Adaption of planned trajectory to deviations in position and speed.

3. Test of adapted trajectory for conflicts.

4. Conflict or significant deviation lead to recalculation of trajectory with respect to current position and speed.
Adaption
Experiment Description

Selected Airport: Generic airport inspired by Munich

- Used for the project the SMAN was developed for.
- Same runway structure with two independent runways as used at many European airports (London Heathrow, Athen-Eleftherios, Oslo Gardermoen).
- Munich is an A-CDM Airport with a high amount of available data.

Experiment Environment:

- Combination of CADEO and TRACC with the traffic simulator NARSIM within DLR ATS360 real time simulator.
- TRACC works non-deterministic.
- All necessary commands were generated by TRACC and send to NARSIM (clearances, taxi and speed commands).
- Pseudo-realistic behavior created by different simulation of aircraft (breaking / accelerating) and pilot behavior (delayed reactions) for NARSIM and TRACC.
System Design

- **TRACC** Surface Management System
- **CADEO** Departure Management System
- **SimNet** (Middleware)
- **NARSIM** Air Traffic Simulator

Aircraft Commands

Air Traffic (Flightplans, Aircraft...)

- RLUT
- TLUT
- TOBT
- TTOT
- TLUT
Layout and Traffic Flow

33 Arrivals per Hour
17 Departures per Hour
## Results: Example of TRACC Output

<table>
<thead>
<tr>
<th>Code</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLUT adapted (73)</td>
<td>TLUT adapted by 73 seconds compared to last ELUT</td>
</tr>
<tr>
<td>TTOT adapted (99)</td>
<td>TTOT adapted by 99 seconds in comparison to last TTOT</td>
</tr>
<tr>
<td>TSAT adapted (72.0)</td>
<td>Adapt TSAT by 72 sec. for avoiding idle times on airfield (slow taxi, queues)</td>
</tr>
<tr>
<td>TOA</td>
<td>Carry out &quot;Time Optimization Algorithm&quot; [12]</td>
</tr>
<tr>
<td>TLUT adapted (-98)</td>
<td>TLUT adapted whilst optimizing</td>
</tr>
<tr>
<td>TTOT adapted (-99)</td>
<td>TTOT adapted whilst optimizing</td>
</tr>
<tr>
<td>(Break)</td>
<td>Stop optimization and start again with new values.</td>
</tr>
<tr>
<td>TOBT Push-back conflict (55)</td>
<td>Push-back conflict is still the same</td>
</tr>
<tr>
<td>TSAT adapted (-72.0)</td>
<td>Adapt TSAT to changed TLUT but not below TOBT</td>
</tr>
<tr>
<td>TOA</td>
<td>Carry out &quot;Time Optimization Algorithm&quot;</td>
</tr>
<tr>
<td>RLUT Calculation (small)</td>
<td>Carry out RLUT-Calculation with speed increase as far as possible</td>
</tr>
</tbody>
</table>
Results: Adaptation Caused by CADEO
Results: Adaption Caused by TRACC

TSAT / RLUT / ELUT / TLUT for BAW1549 with one adaption caused by TRACC
## Results: Number and Type of TSAT Adaptions

<table>
<thead>
<tr>
<th>Run / REASON</th>
<th>Pushback Conflict</th>
<th>TLUT Adaption</th>
<th>Pushback Conflict and TLUT-Adaption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>
### Results: Average Difference Between TOBT And TSAT (Pushback-Delay)

<table>
<thead>
<tr>
<th>Run</th>
<th>Number affected AC</th>
<th>Number Adoptions</th>
<th>Avg. Delay TSAT / All Adapt. [s]</th>
<th>Avg. Delay last TSAT / Affect. Dep.[s]</th>
<th>Avg. Delay last TSAT / All Dep.[s]</th>
<th>Taxi Time Difference to VTT [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>23</td>
<td>144.6</td>
<td>136.6</td>
<td>104.5</td>
<td>-55</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>28</td>
<td>119.8</td>
<td>122.7</td>
<td>108.3</td>
<td>-63</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>26</td>
<td>140.3</td>
<td>141</td>
<td>107.8</td>
<td>-61</td>
</tr>
</tbody>
</table>

Combination of TRACC and CADEO has led to a more smooth traffic flow by intensive action.

TLUT adaptions result in holding of aircraft at parking positions.

Average taxi speed were higher than for typical standard trajectories.
## Results: Reasons for new or adaption of trajectories

<table>
<thead>
<tr>
<th>Change Group</th>
<th>Type</th>
<th>Average Number / Run</th>
<th>Average Number / AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD&amp;R adaption</td>
<td>New trajectory</td>
<td>13.7</td>
<td>0.3</td>
</tr>
<tr>
<td>all flights</td>
<td>Adapted trajectory</td>
<td>119.7</td>
<td>2.4</td>
</tr>
<tr>
<td>TLUT-change (departures only)</td>
<td>New trajectory</td>
<td>63.3</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>Unchanged trajectory</td>
<td>30.3</td>
<td>1.8</td>
</tr>
</tbody>
</table>

### Reasons for New Trajectory

<table>
<thead>
<tr>
<th>CD&amp;R-reasons for creating new trajectories</th>
<th>Type</th>
<th>Average Number / Run</th>
<th>Average Number / AC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Route or speed deviation leading to conflicts</td>
<td>9</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Route deviation (no conflict)</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Deviation speed profile (no conflict), missed target time</td>
<td>3.7</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Results: Difference between TLUT and ELUT

<table>
<thead>
<tr>
<th>TLUT – ELUT</th>
<th>All Adaptors (281) [s]</th>
<th>Last entry for affected. AC (51) [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>8.5</td>
<td>11.8</td>
</tr>
<tr>
<td>Variance</td>
<td>17.4</td>
<td>24.3</td>
</tr>
<tr>
<td>Minimum</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

Implication

Higher values in the right column are caused by the mechanism of avoiding a new trajectory creation as long as |TLUT-ELUT| < 30s.

Most departures will arrive at the runway a short time before the line-up clearance will be given.

TRACC is able to stay close to the given TLUT time.
### Conclusions

Coupling of CADEO and TRACC has shown the feasibility of the coupling concept for SMAN and DMAN using 4D trajectories.

A smoother traffic flow was created by CADEO and maintained by TRACC through CD&R and adaption.

CD&R and trajectory adaption should be important parts of each SMAN – DMAN Coupling.

Conflict-detection, resolution and trajectory adaption lead to a high number of re-calculation.

A negotiation between SMAN and DMAN must be carried out to prevent loss of benefit acquired before.

### Next Steps/ Open Questions

CADEO should include ELUTs created by TRACC in the calculation of the optimal departure sequence (in addition to RLUT).

Similar tests should be executed with a more complex airport as fast-time simulations and with a direct connection between CADEO and TRACC.
Thank you for your interest

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