A Scheduling Algorithm Compatible with a Distributed Management of Arrivals in the National Airspace System

Alexander V. Sadovsky
Robert D. Windhorst

NASA Ames Research Center

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Context: Arrival Scheduling

Standard Terminal Arrival Routes (STARs)
Goals

• Explore the potential benefits of a distributed system (service-oriented architecture)

• Enable an airline operator to:
  ▪ influence its schedule...
  ▪ ...toward its business objectives
  ▪ keep objectives undisclosed
  ▪ re-negotiate a schedule
Outline

• Background: Arrival Scheduling
• Goals
• Context
• Definition of a “schedule”
• Computation of a schedule
Context

• Research of options for a 2045+ Air Traffic Control system
• NOT an advocacy for a distributed system
• Currently: scheduling algorithms used as part of Traffic-Based Flow Management (TBFM)
• Collaborative Decision Making (CDM)
What is a *schedule*?

- Along a flight’s route, pick nodes.
- At each node, compute a Scheduled Time for flight to Arrive (STA).

A schedule:

<table>
<thead>
<tr>
<th>Node</th>
<th>⋮</th>
<th>$n$</th>
<th>⋮</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduled Time of Arrival (STA)</td>
<td>⋮</td>
<td>STA$^n$</td>
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</table>
What is a schedule?

• The STAs are the decision variables

• What constrains the decisions?
  
  – traffic

  – flight performance

  – weather
Type 1: Node constraints

• STA no earlier than the *Estimated Time of Arrival*: 
  \[ STA \geq ETA \]

• Time separation:
  \[ STA_{f_2}^n - STA_{f_1}^n \geq (\text{minimal required sep’}n) \]
Type 2: Link constraints

- Bounds on travel time:

  \[(\text{shortest t.t.}) \leq \text{STA}_{f}^{n1} - \text{STA}_{f}^{n2} \leq (\text{longest t.t.})\]

- Some links: no passing

  \[\text{STA}_{f_{1}}^{n1} \leq \text{STA}_{f_{2}}^{n1} \implies \text{STA}_{f_{1}}^{n2} \leq \text{STA}_{f_{2}}^{n2}\]
Effects of node constraints

scheduling flight $f$

![Diagram showing the effects of node constraints on scheduling a flight. The diagram illustrates the STAs of previously scheduled flights and nodes available for scheduling.](image)
Effects of Constraints: Travel time limitations can... make a time window unreachable downstream:

The only time window reachable by leaving node $k$ at time $T^k$. 

![Graph showing time windows and node travel.](image)
Effects of Constraints: Travel time limitations can...

...make an upstream time window uncontrollable:
Scheduling Algorithm: Input

- A list of flights, ordered by priority
- Each flight has:
  - A sequence of nodes
  - A given ETA at first node
  - Aircraft type (separation)
  - Bounds on travel speed (t. t. bounds)
Scheduling Algorithm, Phase 1: Times Blocked by Prior Flights’ STAs
Scheduling Algorithm, Phase 2: Effects of Travel Speed Bounds
Scheduling Algorithm, Phase 3: Pairing **Available Time Intervals**

- **node 1**
- **2**
- **3**
- **4**
Scheduling Algorithm, Phase 3: Pairing Available Time Intervals
Scheduling Algorithm, Phase 4: Sequences of Time Intervals
Scheduling Algorithm, Phase 4: Sequences of Time Intervals
Scheduling Algorithm, Phase 5: Pick a Feasible Sequence
Scheduling Algorithm, Phase 5: Pick a Feasible Sequence
Scheduling Algorithm, Phase 6: Pick the STAs to objective

Objective: ASAP

node 1

STA

STA

STA

STA

2

3

4
Scheduling Algorithm, Phase 6: Pick the STAs to objective

Objective: fuel efficiency
Scheduling Algorithm, Phase 6: Ensure constraint compliance

Node  

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node 1  

2  

3  

4  

STA  

STA
A Computed Example

arrival fix

runway

arrival fix

arrival fix
A Computed Example

Flight 0: B777
NODE: 1 0 5 3
ETA: 2.1 71.46 113.54 146.26
STA: 2.1 71.46 113.54 146.26

Flight 1: B737
NODE: 2 3
ETA: 68.27 148.19
STA: 71.34 151.26

Flight 2: B777
NODE: 4 3
ETA: 115.14 148.26
STA: 123.14 156.26
A Computed Example

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Distributed System Functionality

distributed record of the already scheduled flights

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<td>$\text{STA}(i, f_m)$</td>
</tr>
<tr>
<td>$i$</td>
<td>$f_n$</td>
<td>$\text{STA}(i, f_n)$</td>
</tr>
<tr>
<td>$j$</td>
<td>$f_m$</td>
<td>$\text{STA}(j, f_m)$</td>
</tr>
<tr>
<td>$\vdots$</td>
<td>$\vdots$</td>
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### Distributed System Functionality

#### Schedule Service Supplier
For the Operator of a Flight $f$

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**distributed record of the already scheduled flights**
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Which flights use nodes needed by $f$?

**Schedule Service Supplier**
For the Operator of a Flight $f$
Distributed System Functionality

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Schedule Service Supplier
For the Operator of a Flight $f$

Schedule Service Supplier
For the Operator of another Flight

distributed record of the already scheduled flights
Summary

• An algorithm for the generic step in scheduling.

• Requires knowing prior schedules.

• Can be run by each agent in a distributed system.
Future research questions

• How to prioritize flights?

• Different operators’ objectives:
  – Systemic inefficiencies?
  – Criteria of equity and fairness?

• How to implement re-negotiation of a schedule?

• How to ensure a negotiation ends?

• Race conditions between Service Suppliers accessing distributed record?
Thank you!

Q&A
Terminal Sequencing and Spacing

“The TMA-TM generates an arrival schedule that conditions the flow in the Center to facilitate sequencing and spacing in the TRACON. [...] [The Center controllers’] radar displays show meter lists and delay countdown timers (DCTs) with a resolution of tenths of minutes. TRACON controllers are presented with CMS advisory tools to assist schedule conformance.”

Thipphavong et. al., 32nd DASC, Syracuse, NY, 2013.
Collaborative Decision Making

“XYZ AIRLINE: NEW YORK METROS SURROUNDED BY SIGNIFICANT AMOUNT OF CONVECTION FOR MANY HOURS. THEY TACTICALLY MOVED A LOT OF AIRPLANES, USED LIMITED GROUND STOPS AND HAD A GDP THAT SERVED THEM WELL. A VERY GOOD JOB AND WE APPRECIATE HELPING XYZ1234 DFW-LGA FROM DIVERTING.”

Source: