A Baseline for Terminal Airspace Design Assessment

Tobias Andersson Granberg
Valentin Polishchuk

Billy Josefsson
Flights on Apr 30 2013
Congestion hotspots: Airports

Sweden’s 3 largest airports:
- Arlanda
- Gothenburg
- Bromma
Stockholm TMA (1958)

Stockholm TMA (now)

1990’s --

Historical layout

- Experts opinion
- Hands-on patching
- Rule-of-thumb
- No global outlook
Stockholm TMA (future)?

2012 --

LFV’s systematic study

- improve the design with optimization tools
- clean sheet approach
- explore operational concepts
ODESTA Project

• Optimal DESign of Terminal Airspace
• Linköping University +LFV
  + reference group
• Funding for 2015--2018
  – Swedish Gov. Agency for Innovation Systems
This talk

● (One possible) step towards operations optimization
  ○ single aspect

● Feeders <-> entry/exit points assignment
  ○ capacitated matching
  ○ different paradigms
Why such a study?

HUGE optimization problem

How to deal?
Split into

- subproblems
- components
- layers
- …
TMA design

Matching

- demand
  - arrivals
  - departures

- resources
  - available airspace
  - RWYs

(with help of middleware)
STARS, SIDs, sectors, …
Our focus

Outer rim

- demand
  - arrivals
  - departures

- resources
  - entry/exit points
  - considered fixed, given
Problem shaping up

Output

entry/exit point for each flight

Input

- resources
  - entry/exit points
- demand
  - ?
Demand

Mining historical data

- EUROCONTROL’s DDR2
- .so6: SAAM 4D trajectories last filled flight plans
- to/from S-TMA in 2014

Other possible demand definitions

- Simulated demand
  - x2, x3, ...
- Projected demand
  - Random process, …
For each flight

Extract

- last point before TMA entrance for in-flights
- first point after TMA exit for out-flights

Call it **feeder**

Path before/after feeder -- outside TMA designer interest
Minor cleanup

Excluded flights

- not through an echart point
- circular
- ESCM, ESOW, ESSU
  - small airfields in the TMA
- …

~200 flights overall
**Major cleanup**

**Preprocessing: Feeder usage statistics**

- **# of aircraft**
- **# of feeders**

Feeders:

- "Pareto-like" distribution

- <10% flights, in any time interval
Demand

Flights through 40 feeders, for each flight $f$

- feeder $F(f)$
- RWY($f$)
- time at $F(f)$
- in/out
- a/c type
- …
Demand

Flights through 40 feeders, for each flight $f$

- feeder $F(f)$
- RWY($f$)
- time at $F(f)$
- in/out
- a/c type
- ...

Resource

Entry/exit points

Assignment
Before assignment...

“Airline dream”: Great Circle path

\[ \text{GCD}(f) = \text{GCD}(F(f), \text{RWY}(f)) \]

\[ \text{GCDF} = \sum_f \text{GCD}(f) \]

Far from reality, “ATCOs nightmare”, ignores even entry/exit points, …
**GCD-Greedy**

“Airline dream” s.t. use of entry/exit pts

\[ w(F(f), E) = \text{GCD}(F(f), E) + \text{GCD}(E, \text{RWY}(f)) \]

\[ \text{GCD-Greedy}(f) = \min_E w(F(f), E) \]

\[ \text{GCD-Greedy} = \sum_f \text{GCD-Greedy}(f) \]

Unstructured FF in TMA, “ATCOs bad dream”, …
**Current-Greedy**

"Airline dream" s.t. use of entry/exit pts and STARs/SIDs

\[ w(F(f),E) = \text{GCD}(F(f),E) + \text{Current}(E,\text{RWY}(f)) \]

Current-Greedy(f) = \( \min_E w(F(f),E) \)

Current-Greedy = \( \sum_f \text{Current-Greedy}(f) \)

Structured flow in TMA, but potentially overloaded points…
Points usage statistics

- GCD-Greedy
- Current-Greedy

![Graph showing max point load and number of hours with max load for GCD and Current-Greedy algorithms.]

max point load (# of aircraft) vs # of hrs with max load
Capacity constraints

- Split time into intervals of length $T = 1$ hr
  - standard in ATM?
  - $T = 30$ min, 1.5 hr are OK too
  - rolling horizon (20/60 min)
  - ... 

- Within every interval any entry / exit point has
  \[ \leq N = 7 \text{ flights} \]
  - historical max load (2014)
  - just total, separation ignored
  - cost($N$) dependence below
Minimum-weight capacitated one-side-perfect matching in weighted complete bipartite graph

Graph on 2 sets (bipartite)
- edge between any $F, E$ (complete)
- $w(F, E)$: edge weight (weighted)

(N-)Matching: set of edges, s.t.
- any $F$ incident to an edge of $M$ (perfect)
- any $E$ incident to $\leq N$ edges of $M$ (capacitated)

Min-weight matching (w-min N-matching): N-matching with min total edge weight

Efficient algorithms exist (reduce to mincost flow)
**GCD-Match**

\[ w(F(f),E) = \text{GCD}(F(f),E) + \text{GCD}(E,RWY(f)) \]

For each hour \( h \)

\[ M^*_h = \text{w-min N-matching} \]

\[ \text{GCD-Match} = \sum_h M^*_h \]

No overloaded points, but unstructured FF in TMA ("ATCOs bad dream"), …
Current-Match

\[ w(F(f), E) = GCD(F(f), E) + \text{Current}(E, RWY(f)) \]

For each hour \( h \)

\[ M^*_h = \text{w-min 7-matching} \]

Current-Match =

\[ \sum_h M^*_h \]
**Current-Current**

Actual (historical) flown distance

\[
\text{Current-Current}(f) = \text{GCD}(F(f), E(f)) + \text{GCD}(E(f), \text{RWY}(f))
\]

\[
\text{Current-Current} = \sum_f \text{Current-Current}(f)
\]
<table>
<thead>
<tr>
<th></th>
<th>GCD</th>
<th>STARs/SIDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greedy</td>
<td><strong>GCD-Greedy</strong></td>
<td><strong>Current-Greedy</strong></td>
</tr>
<tr>
<td>Coordinated</td>
<td><strong>GCD-Match</strong></td>
<td><strong>Current-Match</strong></td>
</tr>
</tbody>
</table>

**Diagram:***

- **Current-Current**
- **F(f)**
- **E(f)**
- **GCD-Match** entry/exit
- **Current-Greedy** entry/exit
- **GCD-Greedy** entry/exit
- **RWY(f)**
<table>
<thead>
<tr>
<th></th>
<th>GCD</th>
<th>STARs/SIDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greedy</td>
<td>GCD-Greedy</td>
<td>Current-Greedy</td>
</tr>
<tr>
<td>Coordinated</td>
<td>GCD-Match</td>
<td>Current-Match</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>GCD</th>
<th>STARs/SIDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCDF</td>
<td>15921330</td>
<td>85.6</td>
</tr>
<tr>
<td>GCD-Greedy</td>
<td>15992796</td>
<td>86.0</td>
</tr>
<tr>
<td>Current-Greedy</td>
<td>17564138</td>
<td>94.5</td>
</tr>
<tr>
<td>GCD-Match</td>
<td>16031315</td>
<td>86.2</td>
</tr>
<tr>
<td>Current-Match</td>
<td>17762601</td>
<td>95.5</td>
</tr>
<tr>
<td>Current-Current</td>
<td>18799869</td>
<td>101.1</td>
</tr>
<tr>
<td>Method</td>
<td>Cost</td>
<td>Stretch Factor</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>GCD-Fixed</td>
<td>15921330</td>
<td>85.6</td>
</tr>
<tr>
<td>GCD-Greedy</td>
<td>15992796</td>
<td>86.0</td>
</tr>
<tr>
<td>Current-Greedy</td>
<td>17564138</td>
<td>94.5</td>
</tr>
<tr>
<td>GCD-Match</td>
<td>16031315</td>
<td>86.2</td>
</tr>
<tr>
<td>Current-Match</td>
<td>17762601</td>
<td>95.5</td>
</tr>
<tr>
<td>Current-Current</td>
<td>18799869</td>
<td>101.1</td>
</tr>
</tbody>
</table>
**GCD-Match – GCD-Greedy:** human factors

**Current-Match – Current-Greedy:** similar (sector load ignored)

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GCDF</strong></td>
<td>15921330</td>
<td>85.6</td>
</tr>
<tr>
<td><strong>GCD-Greedy</strong></td>
<td>15992796</td>
<td>86.0</td>
</tr>
<tr>
<td><strong>Current-Greedy</strong></td>
<td>17564138</td>
<td>94.5</td>
</tr>
<tr>
<td><strong>GCD-Match</strong></td>
<td>16031315</td>
<td>86.2</td>
</tr>
<tr>
<td><strong>Current-Match</strong></td>
<td>17762601</td>
<td>95.5</td>
</tr>
<tr>
<td><strong>Current-Current</strong></td>
<td>18799869</td>
<td>101.1</td>
</tr>
</tbody>
</table>
**GCD-Greedy − GCDF**: cost of flying in/out via the pts small (pts spread evenly around); Feeders--Points graph is a good *spanner*

<table>
<thead>
<tr>
<th>Method</th>
<th>Value</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCDF</td>
<td>15921330</td>
<td>85.6</td>
</tr>
<tr>
<td>GCD-Greedy</td>
<td>15992796</td>
<td>86.0</td>
</tr>
<tr>
<td>Current-Greedy</td>
<td>17564138</td>
<td>94.5</td>
</tr>
<tr>
<td>GCD-Match</td>
<td>16031315</td>
<td>86.2</td>
</tr>
<tr>
<td>Current-Match</td>
<td>17762601</td>
<td>95.5</td>
</tr>
<tr>
<td>Current-Current</td>
<td>18799869</td>
<td>101.1</td>
</tr>
</tbody>
</table>
Current – $GCDF$: overall cost of control

~ price of anarchy: best centralized outcome / best individualized outcome

<table>
<thead>
<tr>
<th>Method</th>
<th>Cost</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCDF</td>
<td>15921330</td>
<td>85.6</td>
</tr>
<tr>
<td>GCD-Greedy</td>
<td>15992796</td>
<td>86.0</td>
</tr>
<tr>
<td>Current-Greedy</td>
<td>17564138</td>
<td>94.5</td>
</tr>
<tr>
<td>GCD-Match</td>
<td>16031315</td>
<td>86.2</td>
</tr>
<tr>
<td>Current-Match</td>
<td>17762601</td>
<td>95.5</td>
</tr>
<tr>
<td>Current-Current</td>
<td>18799869</td>
<td>101.1</td>
</tr>
</tbody>
</table>
Greedy: overloaded_hrs(N)

N = 7 : ~1/2 of hrs are overloaded

**GCD-Greedy**

**Current-Greedy**
Matching: cost(N)

High sensitivity to N around N=10-15

**GCD-Match**

**Current-Match**
Summary

- Subproblem in TMA optimization
  - feeders--entry/exit points matching
- Local flow modification
  - keep the rest intact
- How much is the control?
  - where efficiency may be lost/gained
  - room for improvement
- Applicable to any TMA
  - human decides T and N
  - the rest is (almost) automated

Extensions

- Weigh distance w.r.t. a/c type
  - not all a/c are equal
  - noise, not only distance
- Bound sector load
  - not single point load
- Optimize entry/exit points locations
  - don’t keep them fixed
- Re-sectorize
  - better locate the pts and
  - sector boundaries balance workload
Happy Matchings!

Tobias Andersson Granberg
Valentin Polishchuk
firstname.lastname@liu.se

Billy Josefsson
S-TMA (with a BMA STAR and SID)