Resource Rationing and Exchange Methods in Air Traffic Management

Michael Ball
R.H. Smith School of Business & Institute for Systems Research
University of Maryland
College Park, MD

joint work with Thomas Vossen
Motivation for Ground Delay Programs: airline schedules “assume” good weather

SFO: scheduled arrivals:
VMC airport acceptance rate:
IMC airport acceptance rate:
Ground Delay Programs

- delayed departures
- delayed arrivals/
  no airborne holding
- delayed departures
- delayed departures
Collaborative Decision-Making

Traditional Traffic Flow Management:
• Flow managers alter routes/schedules of individual flights to achieve system wide performance objectives

Collaborative Decision-Making (CDM)
• Airlines and airspace operators (FAA) share information and collaborate in determining resource allocation; airlines have more control over economic tradeoffs

CDM in GDP context:
• CDM-net: communications network that allows real-time information exchange
• Allocation procedures that increase airline control and encourage airline provision of up-to-date information
GDPs under CDM

Resource Allocation Process:

- FAA: *initial “fair” slot allocation* [Ration-by-schedule]
- Airlines: *flight-slot assignments/reassignments* [Cancellations and substitutions]
- FAA: *periodic reallocation to maximize slot utilization* [Compression]

Note:
- *reduced capacity is partitioned into sequence of arrival slots*
- *ground delays are derived from delays in arrival time*
Issues

• What is an ideal (fair) allocation?

• How can an allocation be generated that is very close to the ideal while taking into account dynamic problem aspects?

• How can airlines exchange resources they receive as part of their allocation?
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Determining fair shares

Sketch:

• Assume slots are *divisible*
  – leads to probabilistic allocation schemes

• Approach: impose properties that schemes need to satisfy
  – fairness properties
  – structural properties (consistency, sequence-independence)
Allocation Principles

How to allocate limited set of resources among several competing claimants???

First-come, first-served: strict priority system based on OAG times ⇔ RBS

Equal access: all claimants have equal priority ⇔ % slots received by airline = % flights scheduled in time period
Comparison

• First-come/first-served – RBS:
  – implicitly assumes there are enough slots to go around, i.e. all flights will be flown
  – lexicographically minimizes max delay
  – implicitly treats flights as independent economic entities

• Equal Access:
  – implicitly assumes there are not enough slots to go around – some flight/airlines will not receive all the slots they need
  – does not acknowledge that some flights cannot use some slots
  – strict interpretation leads to Shapley Value
Equal Access to Usable Slots: Proportional Random Assignment (PRA)

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Empirical Comparison

Deviation PRA vs. RBS (LaGuardia)

- On the aggregate, both methods give similar shares
- No systematic biases
Issues

- What is an ideal (fair) allocation?
- How can an allocation be generated that is very close to the ideal while taking into account dynamic problem aspects?
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GDPs as Balanced Just-in-Time Scheduling Problem

- Airlines = products, flights = product quantities
- Minimize deviation between “ideal” rate and actual production
GDP Situation

Questions:
- What are appropriate “production rates”?
- How to minimize deviations?
- Managing program dynamics
“Release times” defined by scheduled arrivals

Questions:
- What are appropriate “production rates”? **ANS: RBS**
- How to minimize deviations?
- Managing program dynamics
Models and Algorithms for Minimizing Deviation from Ideal Allocation

• General class of problems: minimize deviation between actual slot allocation and ideal slot allocation
  
  Variants based on:
  – Objective function (deviation measures)
  – Constraints on feasible allocations

• Minimize cumulative/maximum deviation:
  – complex network flow model (based on JIT scheduling models) can solve most variants

• Minimize sum of deviations between jth slot allocated to airline \(a\) and ideal location for airline \(a\)’s jth slot:
  – Assignment model
  – Greedy algorithm for several cases
GDPs and Flight Exemptions

- GDPs are applied to an “included set” of flights
- Two significant classes of flights destined for the airport during the GDP time period are exempted:
  - Flights in the air
  - Flights originating at airports greater than a certain distance away from the GDP airport
- Question: Do exemptions induce a systematic bias in the relative treatment of airlines during a GDP??
Flight exemptions introduce systematic biases:
- USA (11m/ft), UCA (18m/ft) “lose” under exemptions
Reducing Exemption Bias

Objective:
• Use deviation model to mitigate exemption bias
  – i.e. “inverse” compression

Approach:
• RBS applied to all flights whose arrival times fall within GDP time window \(\Rightarrow\) ideal allocation
• Set of exempted flights are defined as before (there are good reasons they are exempted)
• Time slots given to exempted flights “count against” allocation
• Delays allocated to non-exempted flights so as to minimize overall deviation from ideal allocation
Flight Exemptions

- Minimize deviations using optimization model that incorporates exemptions
- reduces systematic biases, e.g. USA from 11m/flt to 2m/flt, UCA from 18m/flt to 5m/flt
Discussion

• Define “ideal” allocation
• Manage program dynamics based on models that minimize deviation of actual slots allocated from ideal allocation
• Provides single approach to both RBS and compression
• Provides approach for mitigating bias due to exemptions
• Other potential application, e.g. handling “pop-ups”
Issues

- What is an ideal (fair) allocation?
- How can an allocation be generated that is very close to the ideal while taking into account dynamic problem aspects?
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Why Exchange Slots??

Earliest time of arrival:
4:15

- AAL350 4:50
- AAL235 5:10

XX AAL355 4:00

Slot made available by canceled or delayed flight
Earliest time of arrival: 4:15

Current Procedure: Compression

XX  AAL355  4:00
UAL205  4:05
DAL254  4:10
USA105  4:15

AAL350  4:50

AAL235  5:10
Current Procedure: Compression

Earliest time of arrival: 4:15

- UAL205 4:00
- DAL254 4:05
- USA105 4:10
- AAL350 4:15
- AAL235 4:50
- AALXXX 5:10
Inter-Airline Bartering

Mediator: FAA

AAL

DAL

UAL

NWA

SWA
Mediated Slot Exchange

- **Offer:**
  - slot_O: slot willing to give up
  - slot_A_1,…, slot_A_n: slots willing to accept in return

- Each airline submits a set of offers
- Mediator determines set of offers to accept and for each accepted offer, the returned slot
Default Offers

earliest time of arrival

slot_{A_n}

slot_{A_1}

slot_O
Offer Associated with Canceled or Delayed Flights

time slot from canceled flight

earliest time of arrival for earliest available flight

occupied time slot

occupied time slot

slot_O

slot_A_1

slot_A_n
Mediation Problem

Input -- list of offers:

slot_O

slot_A_1

slot_A_n
Problem: Which offers to accept
Cycle = set of mutually compatible set of exchanges
Schedule Movements Associated with Cycle
Overall Solution: find non-intersecting set of cycles – problem can be formulated as an assignment problem.

Compression-like solutions can be found using a bi-level objective function (1st level lexicographically minimizes max deviation between early slots released on later slots obtained).
Mediated bartering model suggests many possible extensions:

- Dynamic trading (w conditional offers)
- Alternate mediator objective functions
- K-for-N trades
- Side payments
1-for-1 trades to 2-for-2 trades

- Compression $\Leftrightarrow$ 1-for-1 trading system, i.e. offers involve giving up one slot and getting one in return (many offers processed simultaneously)

- What about k-for-k or k-for-n offers, e.g. 2-for-2:
Formulation of general mediator’s problem as set partitioning problem:

Offer to trade slots 1 & 2 for 3, 4 & 5

Slack variable: slot not traded

Right Hand Side

Set partitioning 0/1 matrix

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Slots, Copy 1

Slots, Copy 2
Possible 2-for-2 trades:

1 up for 1 down: reduce delay on 1 flight/increase delay on another; Model as reduce delay \textit{at least} \(d^-\) on fl in exchange for increasing delay \textit{at most} \(d^+\) on f2.

2 down: reduce delay on two flights; handled by 2 “reduce delay” single flight trades.

2 down: increase delay on two flights; not reasonable.
Formulation of 2-for-2 trading problem as network flow problem w side constraints:
On-Time (Flight) Performance Airline

Performance Function

- Compression Benefits
  - performance improvement if compression executed after flts with excessive delay (>2hrs) are canceled

![Compression Improvement Graph]

- Global Max.
- Compression
Improvement Using 2-for-2 Trading System

• 2-for-2 Trading Model:
  – proposed offers: all at-least, at-most pairs that improve on-time performance

Computational Efficiency:
• 13sec avg.
• 67% solved by LP relaxation
Results for Total Passenger Delay
Airline Performance Function

Max achievable improvement:

改善程度：

改善程度：

Improvement from 2-for-2 trading:
Final Thought: Options for providing airlines ability to trade-off $$ & delay reductions

• Concept 1: Inter-airline slot trading with side payments and slot buying & selling

• Concept 2: Auction long term leases on airport slots with two “levels” of airport capacity

![SCHEDULED ARRIVALS AND CURRENT ARRIVAL RATE BOUNDARIES, REDUCED RATE CONDITIONS](image)

“as-available capacity”

“guaranteed capacity”