GDP$^2$: Grand Design Process for Ground Delay Program

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Trajectory

• Air traffic management family
• Ground Delay Program (GDP)
• Operational challenges in GDP
• A new concept: COuNSEL
• Predictability in GDP
Imbalance between capacity and demand

• Airport
  – Arrival traffic
  – Departure traffic

• En-route
  – Traffic in a sector
  – Flow past a waypoint

(ATAC)
Air Traffic Management—Step 1

• Anticipate imbalance
  – Demand forecast, based on the Enhanced Traffic Management System
    • Flight plans
    • Progress of initiated flights
  – Capacity forecast, depending on the facility
    • Airport capacities (number per unit time): weather condition and runway configuration
    • Sector capacity (number): the ability of human controllers
    • Flow past a waypoint: separation rules or restrictions imposed to meter demand for a downstream sector or airport
Air Traffic Management—Step 2

• Mitigate imbalance by implementing traffic management tools
  – Airport arrivals:
    • Ground Delay Program, Ground Stop
  – Sector traffic:
    • Airspace Flow Program, Re-routing, Miles-in-Trail (MIT) restrictions
  – Waypoint flow:
    • Call for release, time-based metering
  – Airport departures: departure metering technologies
    • CDQM (JFK airport), N-control, SARDA
When and Why
Foggy day

Beautiful view in San Francisco

Low ceiling & poor visibility

SFO
SFO airport

Departure runways

Parallel runways

Single arrival stream

Arrival runways
Ground Delay Program (GDP)

Without GDP

Expensive airborne delay

With GDP

Cheaper and safer ground delay
Statistics

• In 2011
  – 1,065 GDPs were issued in the US
  – applied delay totaling 26.8 million minutes
  – distributed over 519,940 flights
How is GDP born?
Weather forecasts

KSFO 161320Z 161414 19004KT P2SM SCT005
TEMPO 1418 BKN005
FM1900 23010KT P6SM SKC
FM0400 24005KT P6SM SCT015
FM0600 25005KT P6SM BKN012

SFO

Low ceiling & Poor visibility
Strategic telecons

- Participants: flight operators and FAA traffic managers
- Contents: airport called rates (arrivals per hour), GDP scope, GDP duration
• Called rates: 30 arrivals per hour before 11 am and 60 arrivals per hour afterwards
• In practice, they look at 15-min time intervals
GDP initiation

Airport arrivals

excessive demand

 Called rates

scheduled demand profile

Time

7 am 8 9 10 11 noon 1 pm 2 3 4 5
GDP initiation

Airport arrivals

excessive demand

Called rates

If no action, airborne delay

scheduled demand profile

Action:

• holding inbound flights at their origin airports
• releasing them as arrival capacity permits at the destination airport
• Flights scheduled to arrive between 10 am and 5 pm will be assigned Controlled Times of Arrival (CTA’s), also called arrival time slots, to ensure that demand does not exceed capacity.
### Initial assignment of time slots

- **Principle: ration-by-schedule**

<table>
<thead>
<tr>
<th>Flights</th>
<th>Scheduled arrival time</th>
<th>Controlled time of arrival</th>
<th>Scheduled departure time</th>
<th>Controlled time of departure</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAL 536</td>
<td>9:03</td>
<td>10:05</td>
<td>8:03</td>
<td>9:05</td>
</tr>
<tr>
<td>United 547</td>
<td>9:04</td>
<td>10:07</td>
<td>8:04</td>
<td>9:07</td>
</tr>
<tr>
<td>AA 107</td>
<td>9:05</td>
<td>10:09</td>
<td>8:05</td>
<td>9:09</td>
</tr>
<tr>
<td>United 356</td>
<td>9:06</td>
<td>10:11</td>
<td>8:06</td>
<td>9:11</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Change is the only constant
GDP revision by the FAA

- GDP decisions, such as called rates and GDP duration, are made under uncertainty
- These decisions may be revised when the weather condition changes
- A GDP revision is implemented by assigning new time slots to flights
- A revision could be an early GDP cancellation or a GDP extension where more flights will be affected by the program
Collaborative Decision Making (CDM)

• Once a slot is assigned to a flight, the airline operating that flight “owns” the slot

• Intra-airline substitution
  – re-allocate their slots among their flights
  – cancel flights

• Compression (30 min after the initial GDP; 60 min afterwards)
  – Re-assign unused slots (cancellation), when possible to the same airline
  – Otherwise, the slot maybe assigned to another airline

• Slot credit substitution: inter-airline substitution
Slot credit substitution

(Cody Wright, Metron Aviation, Inc.)
GDP movie

First Plan (FAA):
- Report time: 6 am
- Start time: 9 am

Airlines through CDM
- End time: 3 pm

Revised Plan (FAA):
- Revision time: 10 am
- Revised end time: 5 pm
Operational Challenges
Current practice on TMI planning
Challenges

• Flight operators participate in TMI decision making by verbal input. Aggressive operators can sometimes have a disproportionate influence on decisions that affect a broad range of others who are less vocal

• Discussion focuses on specific parameters rather than performance goals

• Different traffic managers may create different plans for the same situation

• The planning process is ad-hoc and subjective
CONsensus user Service Expectation Level (COuNSEL)

Faculty: Michael Ball, Cindy Barnhart, Mark Hansen, Vikrant Vaze
Students and post-doc’s: Yi Liu, Lei Kang, Prem Swaroop, Chiwei Yan
Information to users:
candidate performance vectors

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Efficiency</th>
<th>Predictability</th>
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<tr>
<td>V1: 0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>V2: 0.5</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>V3: 0.7</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Inputs from user 1:
Grades for vectors

Grades
- Excellent
- Good
- Passable

Consensus vector
(service expectation level)

TMI parameters
Performance goals in COuNSEL

• Capacity: maximize throughput
  – Avoid underestimating capacity and encourage quick response if weather clears early

• Predictability: equalize planned delay and realized delay
  – Avoid overestimating/underestimating capacity

• Efficiency: minimize delay cost
  – Take delay on the ground instead of in the air
COuNSEL features

• Airline votes are weighted by number of flights involved in the TMI
• Users can propose performance levels they want to achieve
• Voting process is iterative—new candidate vectors are determined by ratings of previous candidate vectors
• All candidate vectors are feasible—set of feasible vectors is based on conditions of the day
• Airlines may develop their own tools to assess how different candidate vectors affect their individual business objectives
Benefits of COuNSEL

• A more fair and inclusive decision-making process where all the flight operators’ voices will be heard

• A goal-oriented decision-making process where performance criteria are clear to the flight operators

• A more consistent decision-making process where decision are less dependent on managers’ experience and personality
COuNSEL development

Information to users:
candidate performance vectors

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Inputs from user 1:
Grades for vectors

- Grades
  - Excellent
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  - Passable

Consensus vector

TMI parameters
## 1 Performance Vectors

### Possible capacity profiles

<table>
<thead>
<tr>
<th>Planned capacity profiles</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>P11</td>
<td>P12</td>
<td>P13</td>
<td><strong>P1</strong></td>
</tr>
<tr>
<td>C2</td>
<td>P21</td>
<td>P22</td>
<td>P23</td>
<td><strong>P2</strong></td>
</tr>
<tr>
<td>C3</td>
<td>P31</td>
<td>P32</td>
<td>P33</td>
<td><strong>P3</strong></td>
</tr>
</tbody>
</table>

$P_{ij}$ is the realized performance if capacity profiles is planned as $P_i$ but realized as $C_j$.

$P_i$ is the service expectation (candidate performance vector) if C1 is selected as the planned capacity profile.
Answer is available at 1:40 pm in Conference Hall #2
?2 Voting Mechanism
(Prem Swaroop & Mike Ball)

consensus-building.
single winner determination.
practicality.

equitability.
confidentiality.
strategy-resistance.
Feasibility performance vectors, $m$
Grading by Players

**Common** grading language: 0...1

**Assumptions:**
- Concave, non-decreasing value function
- Linear scaling
- Concave, non-decreasing grade function

\[ x_i = g_i(m) = \frac{V_i(m)}{V_i^{\max}} \]
ANSP Input:
Candidates
Weights

Voting mechanism

Consensus vector

Airline Input:
Grades
Candidates

ANSP Processing:
New candidate generation

Feasibility
Constraints
?3 Consensus Vector to GDP Decisions

• On-going work
?3 Airline Cost
(Chiwei Yan, Vikrant Vaze, Cindy Barnhart)

GDP design:
Rate
Duration
Scope

Airline Recovery Module

Airline planned cost

Airline unplanned cost

Airline Cost:
Aircraft delay
Passenger disruption
Crew disruption

Things are always uncertain...
GDP rate may be under/over-estimated
GDP duration may be too long/short
...leads to early cancellation and late extension
additional airborne delay, re-book passengers....
An integrated airline recovery model

Minimize: aircraft delay cost + passenger delay cost

Subject to: flight is covered or cancelled

- one arrival slot can be used by at most one flight
- fleet flow balance

- flight cancel $\Rightarrow$ itinerary disruption
- flight delay $\Rightarrow$ itinerary disruption
- itinerary delay

flight-aircraft constraints

passenger-itinerary constraints
Incorporating Predictability into Cost Optimization for Ground Delay Programs
Airport arrivals

Called rates

Scheduled demand profile
GDP Decisions

• When implementing a GDP, we need to make a plan on when airport arrival capacity will recover to its normal level

• This plan is made based on weather forecast and has uncertainty
  – If capacity recovers earlier than planned, unnecessary delay could be incurred
  – If capacity recovers later than planned, airborne delay could be incurred
Research Literature

• The common objective in GDP design is to minimize the expectation of delay cost, considering two delay components:
  – ground delay
  – airborne delay

  (Richetta and Odoni, 1993; Ball and Lulli, 2004; Mukherjee and Hansen, 2007)

• Previous literature does not consider predictability
Performance Evaluation

Average performance

Throughput
Efficiency
Predictability

(Liu and Hansen, in press)
Why Predictability Matters
## The Behavior of a GDP

- Arrival airport: SFO
- Date: 1/16/2011

### System performance
- Throughput = 0.94
- Efficiency = 0.81
- Predictability = 0.23

(Liu and Hansen, in press)

<table>
<thead>
<tr>
<th>The program</th>
<th>Report time</th>
<th>Affecting arrivals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial plan</td>
<td>6:06 am</td>
<td>8:30 am to 1 pm</td>
</tr>
<tr>
<td>1st revision</td>
<td>9:39 am</td>
<td>8:30 am to 2 pm</td>
</tr>
<tr>
<td>2nd revision</td>
<td>12:10 pm</td>
<td>8:30 am to 4 pm</td>
</tr>
</tbody>
</table>
Flight 6854

Case 1
Before you left home:
‘We are delayed for 40 minutes’
At the terminal:
+ 50 minutes
+ 90 minutes

Case 2
Before you left home:
‘We are delayed for 180 minutes’

In the schedule
Take-off time: 6:08 am

Get ready for: 6:48 am

Get ready for: 9:08 am

same amount of delay,
same cost in previous literature
Flight 6854

Case 1
At the terminal:
‘We are delayed for 2 hours’
- 40 minute

Flight dispatcher: gate conflict?

same amount of delay,
same cost in previous literature

Case 2
At the terminal:
‘We are delayed for 1 hour and 20 minutes’

Flight dispatcher: no gate conflict
Predictability should be appreciated!
Proposed Cost Function

<table>
<thead>
<tr>
<th>In the literature</th>
<th>Incurred</th>
<th>In the proposed work</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ground Delay (GD)</td>
<td>Planned</td>
</tr>
<tr>
<td></td>
<td>Airborne Delay (AD)</td>
<td>Unplanned</td>
</tr>
</tbody>
</table>

- Incurred
  - Planned: GD
  - Unplanned: GD
- Not incurred
  - AD

(References: Richetta and Odoni, 1993; Ball and Lulli, 2004; Mukherjee and Hansen, 2007)
Methodology

Literature: Mathematical programming with discrete math
(Richetta and Odoni, 1993; Ball and Lulli, 2004; Mukherjee and Hansen, 2007)

• requiring detailed inputs about flight schedules and capacity scenarios

• requiring separate simulation runs for different experiment set-ups

Proposed: Scalar optimization based on continuous approximation

• using a small set of key GDP parameters

• studying the relationship between the cost function and GDP decisions in a generic manner
Cost Optimization with GDP No-Revision Model
Continuous Approximation

Cumulative arrivals

1st arrival

2nd arrival

3rd arrival

Actual arrival process

Approximation

Cumulative arrivals

1st arrival - t1
2nd arrival - t2
3rd arrival - t3

Time
Queueing Diagram for GDP

- Scheduled cumulative demand curve
- Planned cumulative arrival curve under GDP
- \( C_L \), planned low airport arrival rate
- \( C_H \), planned high airport arrival rate
- Assigned ground delay in the GDP (absorbed at the departure airport)

Cumulative arrivals

Flight N

Scheduled arrival time

Planned arrival time (Controlled Time of Arrival)

time
Queueing Diagram for GDP

Cumulative arrivals

Scheduled cumulative demand curve

Total planned delay

Planned cumulative arrival curve under GDP

C_H, planned high airport arrival rate

C_L, planned low airport arrival rate

time
Decision on Capacity Recovery Time—$T$

- Cumulative arrivals
- Scheduled cumulative demand curve
- Planned cumulative arrival curve under GDP

Early capacity recovery case
$\tau$: actual capacity recovery time, $< T$

Late capacity recovery case
$\tau$: actual capacity recovery time, $> T$

GDP decision Variable:
- $T$: planned capacity recovery time
GDP Model—No Revision

(Flights take off as planned in the initial GDP plan)

Early capacity recovery case

- Only ground delay
- Incurred = planned

Late capacity recovery case

- Incurred (=planned) ground delay
- Unplanned airborne delay
Cost Optimization, No Revision

\[ E[Cost(\tau, T)] = \]

\[ \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} 1 \cdot \text{planned ground delay}(\tau, T) f(\tau) d\tau \]

\[ + \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} (C_{\text{air}} + \Delta_{\text{un}}) \cdot \text{unplanned airborne delay}(\tau, T) f(\tau) d\tau \]

\( f(\tau) \) is the probability density function of \( \tau \) (uniform distribution).

- Cost coefficient, baseline
- Unpredictability premium
- Cost ratio of airborne delay to ground delay, \( >1 \)
- Late recovery
Optimal Capacity Recovery Time, $T^*$

$$T^* = \frac{[\tau_{min} + (C_{air} + \Delta_{un} - 1) \cdot \tau_{max}]}{C_{air} + \Delta_{un}}$$

- Depend on the distribution of $\tau$ and the cost coefficients
- Does NOT depend on capacity and demand
- $C_{air} + \Delta_{un} \rightarrow 1$
  - Airborne delay and ground delay cost about the same
  - $T^* \rightarrow \tau_{min}$
- $C_{air} + \Delta_{un} \rightarrow \infty$
  - Airborne delay is much more costly than ground delay
  - $T^* \rightarrow \tau_{max}$
Cost Optimization with GDP Revision Model
Early Recovery → Early Cancellation

Cumulative arrivals

Scheduled cumulative demand curve

Updated cumulative arrival curve?

Planned cumulative arrival curve under initial GDP

Planned arrival time (Controlled Time of Arrival)

Scheduled arrival time

Updated Controlled Time of Arrival (actual arrival time)
Flight Status @ Actual Capacity
Recovery Time, $\tau$

Type I: En-route flights

Type II: Flights held on the ground

Type III: Flights scheduled to take off after time $\tau$
New Arrival Demands from Each Type

Type I: En-route flights
Little we can do

Type II: Flights held on the ground
Can take off immediately!

Type III: Flights scheduled to take off after time $\tau$
Can take off at the scheduled departure time instead of the planned departure time
New Total Arrival Demand

For all the flights

Closed-form expressions
Cumulative arrivals
New total demand
$C_H$ (capacity)

For each type of flight
Cumulative arrivals
New

Updated cumulative arrival curve?
Updated Cumulative Arrival Curve

- Arrival curve overlaps with demand curve when capacity is sufficient
- Arrival curve starts to deviate from the demand curve when capacity is lower than demand rate
- Arrival curve overlaps with demand curve after queue clears
Delay Components, Early Cancellation

Cumulative arrivals

Scheduled cumulative demand curve

Updated cumulative arrival curve

Planned cumulative arrival curve under initial GDP

Planned, incurred ground delay

Planned, not incurred ground delay
Late Recovery ➔ GDP Extension

- Giving priority to en-route flights
- Further holding flights on the ground
Delay Components, GDP Extension

- **Cumulative arrivals**
  - Planned cumulative arrival curve under initial GDP
  - Scheduled cumulative demand curve
  - Updated cumulative arrival curve
- **Time**
  - Planned ground delay
  - Unplanned ground delay
  - Unplanned airborne delay
Cost Optimization, GDP Revision Model

\[ E[\text{Cost}(\tau, T)] = \]

\[ \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} 1 \cdot \text{planned ground delay}(\tau, T)f(\tau)d\tau \]

(early recovery, late recovery)

+ \int_{\tau_{\text{min}}}^{T} \Delta_{\text{not}} \cdot \text{planned & not incurred ground delay}(\tau, T)f(\tau)d\tau

(early recovery)

\text{unpredictability premium}

\[ + \int_{T}^{\tau_{\text{max}}} (1+\Delta_{\text{un}}) \cdot \text{unplanned ground delay}(\tau, T)f(\tau)d\tau \]

(late recovery)

\text{unpredictability premium}

\[ + \int_{T}^{\tau_{\text{max}}} (C_{\text{air}}+\Delta_{\text{un}}) \cdot \text{unplanned airborne delay}(\tau, T)f(\tau)d\tau \]

(late recovery)

The optimal capacity recovery time, \( T^* \), is identified by Golden Section Search
## Comparison Table for Cost Coefficients

<table>
<thead>
<tr>
<th>Delay Components</th>
<th>Cost Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Literature</td>
</tr>
<tr>
<td>Planned ground delay</td>
<td>1</td>
</tr>
<tr>
<td>Planned but not incurred</td>
<td>0</td>
</tr>
<tr>
<td>ground delay</td>
<td></td>
</tr>
<tr>
<td>Unplanned ground delay</td>
<td>1</td>
</tr>
<tr>
<td>Unplanned airborne delay</td>
<td>$C_{air}$</td>
</tr>
</tbody>
</table>

Unpredictability premiums: $\Delta_{not}$ and $\Delta_{un}$
Case Study
(GDP Revision Model)
Parameters

- Capacity recovery time is equally likely to be between 2 and 6 hours
- $C_{\text{air}} = 2$
Exemption Ratio

Probability density function of flight time

Exempted

Delayed

0.5 5 7 Flight time (hour)

Early recovery

Planned ground delay

Planned, not incurred ground delay

Probability density function of flight time

Exempted

Delayed

0.5 3.5 7 Flight time (hour)

More recoverable delay
Impact of $\Delta_{un}$ on $T^*$ ($\Delta_{not} = 0$)

- $T^*$ increases with $\Delta_{un}$; larger $\Delta_{un}$, more conservative GDP
- For a given $\Delta_{un}$, $T^*$ increases with the exemption ratio

![Graph showing the impact of $\Delta_{un}$ on $T^*$]
Impact of $\Delta_{\text{not}}$ on $T^*$ ($\Delta_{\text{un}} = 0$)

- $T^*$ decreases with $\Delta_{\text{not}}$; larger $\Delta_{\text{not}}$, more aggressive GDP
- $T^*$ is more sensitive to $\Delta_{\text{not}}$ when the exemption ratio is high
Joint Impact on $T^*$, Fixed Exemption Ratio

$T^*$ is more sensitive to unpredictability premium of unplanned delay as opposed to that of planned but not incurred delay.
Impact on Optimal Cost

• Optimal cost considering predictability

\[ C_p^* = f \left( T^* (\Delta_{not}, \Delta_{up}, ...), \Delta_{not}, \Delta_{up}, ... \right) \]

• Cost when T is optimized ignoring predictability

\[ C_{np} = f \left( T^* (0, 0, ...), \Delta_{not}, \Delta_{up}, ... \right) \]
Cost Savings

Depending on the value of predictability, up to 13% of cost may be saved.
Conclusions

• This work incorporates predictability in GDP cost optimization problem by
  – Distinguishing unplanned delay from planned delay
  – Assigning a non-zero cost to planned but not incurred delay

• Based on continuous approximation and deterministic queueing theory, this work develops two models to connect the objective function with GDP decisions:
  – GDP model with no revision
  – GDP model with one revision
Conclusions

• Results from the case study show that unpredictability premiums clearly matter and have a strong impact on GDP optimal decisions

• Substantial cost penalty may result from focusing only on throughput and efficiency but ignoring predictability in GDP decision making
Future Research Questions

• Value of predictability?
• Value of making an early decision?
Summary

• Ground Delay Program (GDP) is widely used in the United States to manage arrival traffic at airports

• Planning GDP is difficult due to uncertainty in weather and multiple players with conflicting priorities

• In the on-going work, we are developing a new approach to GDP planning based on consensus service expectation level

• Predictability, as an underappreciated performance goal, could be a more important factor in future GDP decision making
Thank you!

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