Incorporating Robustness in Passenger Aviation Planning Models

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Motivation

- Airline scheduling is complex due to lots of interdependent expensive resources.

- To fully utilize resources such as crews and aircraft, airlines develop schedules with minimal slack.

- Plans that are efficient on paper may not be robust in practice.

- Delays can propagate downstream from one flight to another, assuming there is limited buffer between the flights.
Challenging Questions

- How do we assess the robustness of a schedule?
- How do we compute the value of robustness within a schedule?
- How do we incorporate robustness in the planning process?
Our Goals

- Develop metrics for assessing robustness
- Understand the relationship between the structure of a network schedule and the potential for delay propagation
  - Not simulating operational performance
  - Not reviewing historical data
  - Instead, focus on inter-connections between resources in the network plan
Propagation Trees

- Consider the impact of a “root delay”
  - Mechanical failure
  - Ground hold

- How much can an isolated delay impact the rest of the system?
  - Not considering correlations
  - Not considering recovery options (swaps, cancellations...)
  - Focus is on network structure, relationship between plan and potential for propagation
Propagation Tree: Example
Analysis Metrics

- Magnitude – ratio of total propagated delay to original root delay
- Severity – Total number of disrupted flights
- Depth – Length of longest path

Note: Metrics are functions of the root flight delay and its length
Example Revisited

Legend

- Root node
- Nodes with propagated delay (disrupted flights)
- Nodes with no propagation

Root Flight = flight 1
Root Delay = 180
- Total propagated delay = 430
- Severity = 4
- Magnitude = 430/180 = 2.388
- Depth of the tree = 3
- Depth ratio = 3/4 = 0.75
- Split = 2
- Stay = 1
- Grow-out=1
- Split ratio = 2/4 = 0.5

Flight 1
- Origin = A
- Destination = B
- Sched. Dep. = 400
- Sched. Arr. = 500
- Root delay = 180

Flight 2
- cockpit crew
- aircraft

Flight 3
- cockpit crew
- aircraft

Flight 4
- cockpit crew
- aircraft

Flight 5
- cockpit crew
- aircraft
- Origin = C
- Destination = F
- Sched. Dep. = 600
- Sched. Arr. = 700
- Slack = 900-745-35 = 120
- Propagated delay = 50

Flight 6
- cockpit crew
- aircraft
- Origin = B
- Destination = D
- Sched. Dep. = 500
- Sched. Arr. = 775
- Slack = 550-500-35 = 15
- Propagated delay = 185

Flight 7
- cockpit crew
- aircraft
- Origin = F
- Destination = A
- Sched. Dep. = 1090
- Sched. Arr. = 1190
- Slack = 1090-1050-35 = 5
- Propagated delay = 45

Flight 8
- cockpit crew
- aircraft
- Origin = A
- Destination = G
- Sched. Dep. = 1260
- Sched. Arr. = 1390
- Slack = 1260-1150-35 = 75
- No propagated delay

End of pairing
Analysis Procedure

- For each flight and each value of the initial delay (15, 30, ... 180) minutes
  - Construct the propagation tree
  - Keep track of the analysis metrics

- Two carriers
  - One traditional hub-and-spoke carrier
  - One niche “low-fare” carrier
  - Single snapshot in time
Worst-Case Scenarios

- How significant can propagation be?
  - Worst-case severities of 7, 10
  - Worst-case depths of 6, 10
  - Worst-case magnitude 5.78, 6.16

- Observations
  - All associated with 180-minute root delay
  - All are extreme (only 4 flights with severity of 7, one with severity of 10)
  - Very little impact of branching!
### Severity with 180 Minute Root Delay

<table>
<thead>
<tr>
<th>Severity</th>
<th># Flights</th>
<th>% Flights</th>
<th># Flights</th>
<th>% Flights</th>
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<tbody>
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<td>10</td>
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<td>0</td>
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<td>6</td>
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<td>6</td>
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<tr>
<td>5</td>
<td>14</td>
<td>3.41</td>
<td>20</td>
<td>1.16</td>
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<tr>
<td>4</td>
<td>18</td>
<td>4.39</td>
<td>68</td>
<td>3.96</td>
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<tr>
<td>3</td>
<td>36</td>
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<td>201</td>
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<td>65</td>
<td>15.85</td>
<td>303</td>
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<tr>
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<td>24.15</td>
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<td>164</td>
<td>40.00</td>
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<td><strong>100.00</strong></td>
<td><strong>1719</strong></td>
<td><strong>100.00</strong></td>
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*180 minute root delay*
Depth with 180 Minute Root Delay

<table>
<thead>
<tr>
<th>Depth</th>
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<tr>
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* 180 minute root delay
## Depth Ratio with 180 Minute Root Delay

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<th>Depth Ratio</th>
<th># Flights</th>
<th>% Flights</th>
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<th>% Flights</th>
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* 180 minute root delay*
# Magnitude with 180 Minute Root Delay

<table>
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<tr>
<th>Magnitude</th>
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</tr>
</thead>
<tbody>
<tr>
<td>(6, 7]</td>
<td>2</td>
<td>0.49</td>
<td>0</td>
<td>0.00</td>
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<tr>
<td>(5, 6]</td>
<td>3</td>
<td>0.73</td>
<td>3</td>
<td>0.17</td>
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<tr>
<td>(4, 5]</td>
<td>9</td>
<td>2.20</td>
<td>12</td>
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<tr>
<td>(3, 4]</td>
<td>14</td>
<td>3.41</td>
<td>62</td>
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<tr>
<td>(2, 3]</td>
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<td>(1, 2]</td>
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<tr>
<td>0</td>
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</tbody>
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*180 minute root delay*
Severity Across All Delay Lengths

Severity

Severity

percent of the flights

percent of the flights

root delay

root delay

0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

1
0

7
6
5
4
3
2
1
0

15 30 45 60 75 90 105 120 135 150 165 180

15 30 45 60 75 90 105 120 135 150 165 180
Depth Across All Delay Lengths

Depth of the Tree

Depth of the tree

root delay

percent of the flights

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%

15 30 45 60 75 90 105 120 135 150 165 180
Magnitude Across All Delay Lengths

percent of the flights

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
root delay

(5,6] (4,5] (3,4] (2,3] (1,2] (0,1] 0

percent of the flights

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
root delay

(6,7] (5,6] (4,5] (3,4] (2,3] (1,2] (0,1] 0
Conventional Wisdom 1

- CW: “Propagated delays are more significant than the original delays themselves.”
- True or false?
- Both!
  - When delays propagate, the propagated delay can be significantly larger than the initial root delay...
  - ...but lots of delays don’t propagate at all.
    - Off-peak times
    - Crews going off-duty
    - Aircraft going off-rotation
    - End-of-day effects
Magnitude Across All Delay Lengths

Magnitude

percent of the flights

root delay

Magnitude

percent of the flights

root delay
Conventional Wisdom 2

- CW: “A single delay can “snowball” through the entire network.”
- True or false?
- False
  - Buffers keep delays from propagating extensively (i.e. number of impacted flights is contained)
    - Down periods
    - Crews going off-duty
    - Aircraft going off-rotation
    - Crews and aircraft staying together
    - Propagation trees tend to only have one branch
  - Limited numbers of down-stream delays still has significant cost impact
Conventional Wisdom 3

- CW: “Keeping crews and aircraft together can mitigate the impact of disruption.”
- True or false?
- True
  - Most of the “trees” we saw did not actually branch at all
  - Nonetheless there can be significant propagation (e.g. 8 – 10 flights deep in the tree)
  - Can keeping crews and aircraft together ever increase propagation?
Conventional Wisdom 4

☐ CW: “Delays that occur early in the day can cause greater propagation than delays later in the day.”

☐ True or false?

☐ True (on average)
Conventional Wisdom 4
Conventional Wisdom 5

- CW: “It is most important to prevent delays early in the day.”
- True or false?
- False

Diagram:
1. Greatest impact but lowest frequency
2. Lowest impact but greatest frequency
What’s Missing

- Cabin crews
- Passenger itineraries
- International flights
- Correlations
- Recovery operations
- Weighted probabilities of root delays
What Comes Next

- Continue analysis
  - Additional carriers
  - Expand scope
- Assessing value of robustness
- Incorporation in schedule planning
  - Current work in schedule design