The Planning of Ground Delay Programs Subject to Uncertain Capacity

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Advising Committee:

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Source: http://www.apo.data.faa.gov/aspm, 23 May 2006

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  - Ground Delay Programs
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- Initial application
  - Airborne Queue Size
  - Total Delay Cost
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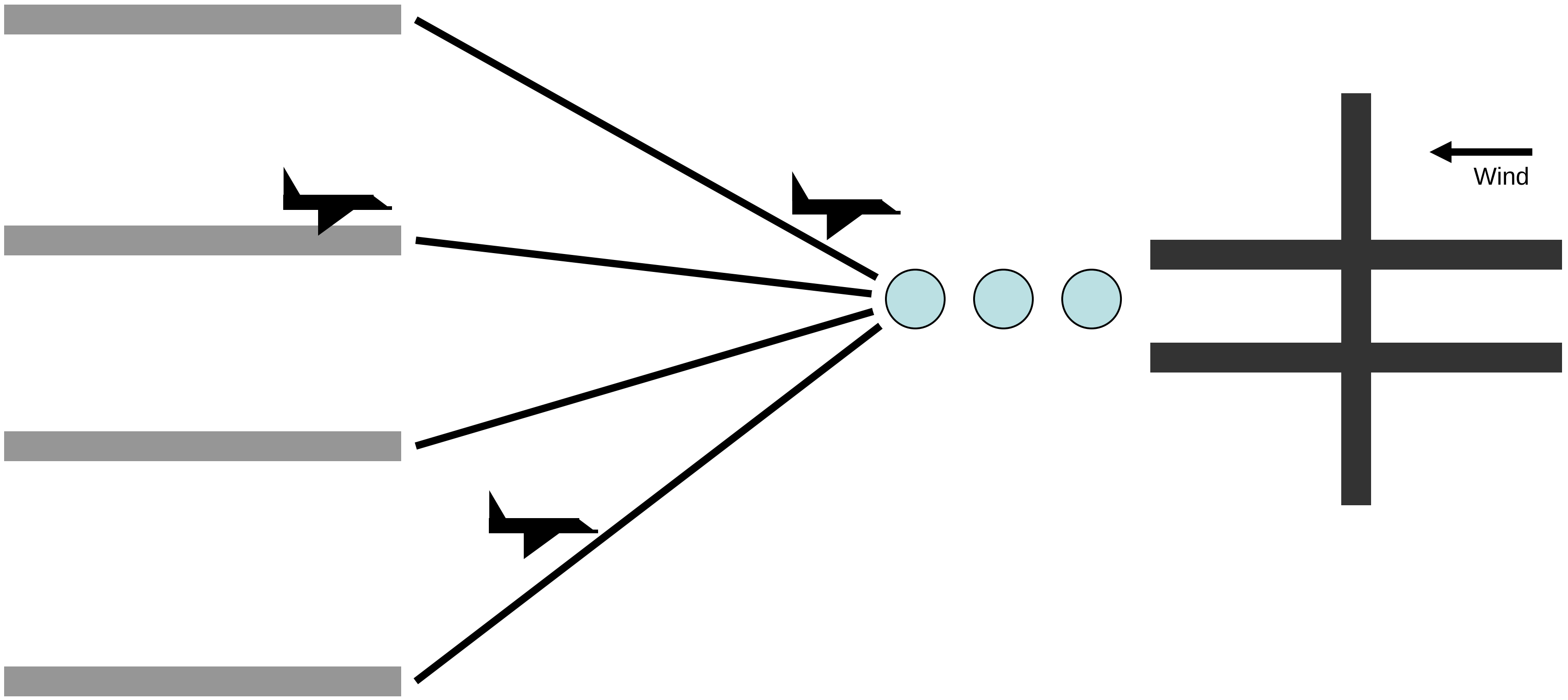
- Conclusions

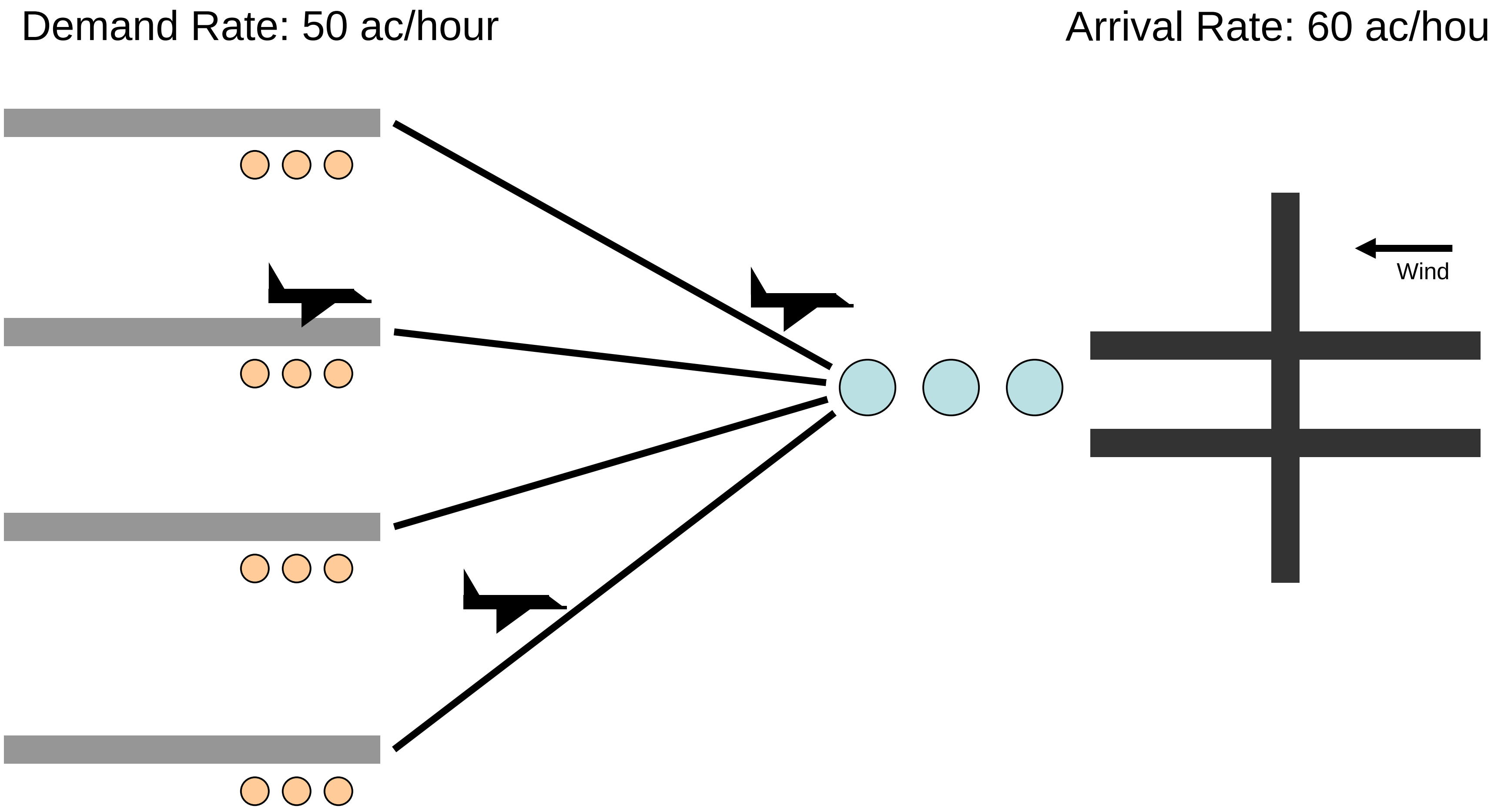
Delays occur when arrival demand exceeds capacity

Demand Rate: 50 ac/hour

Arrival Rate: 60 ac/hour



GDPs create ground delays to avoid those in the air



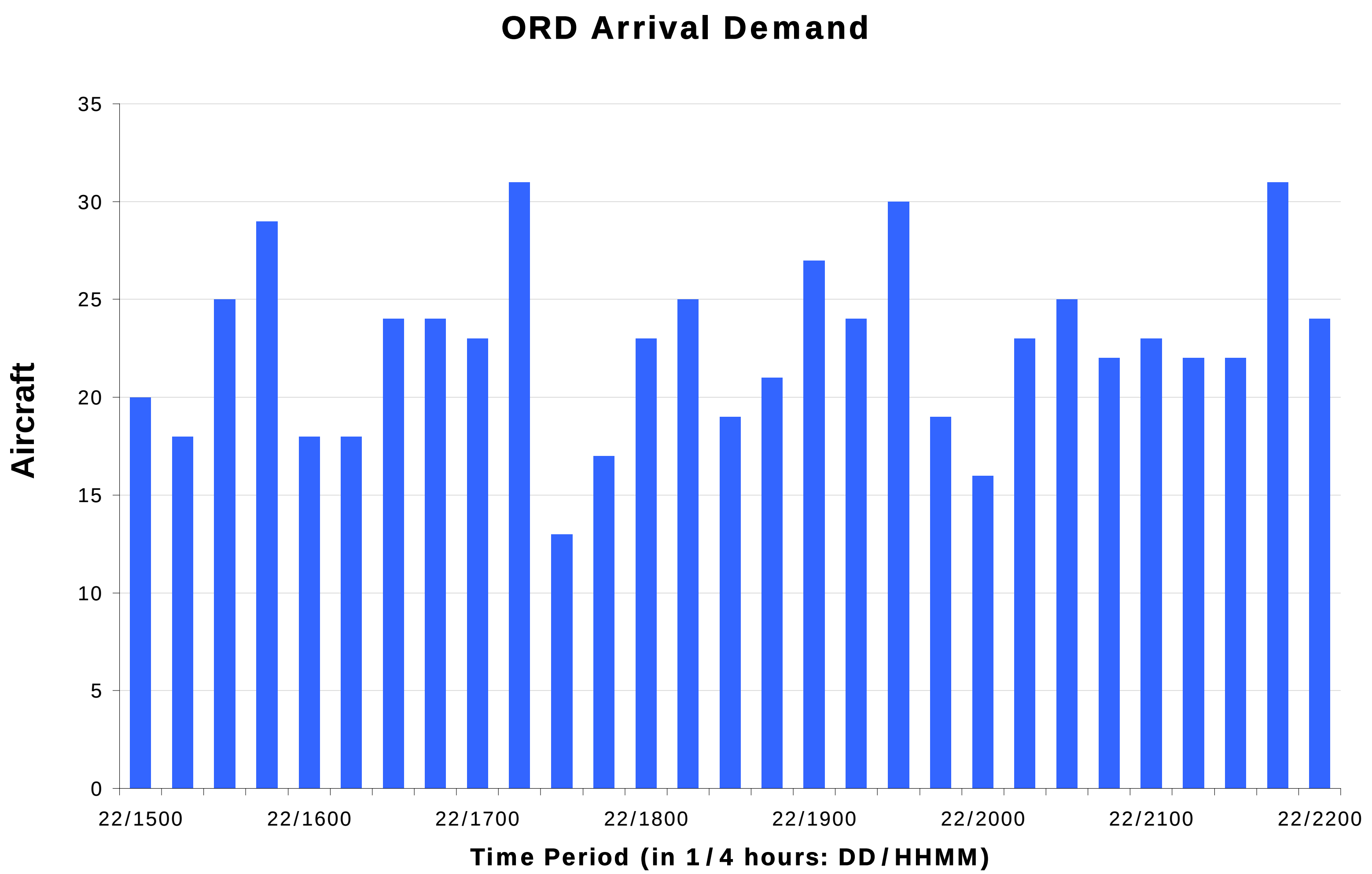
GDP design balances two key tradeoffs

- How much ground delay should be assigned?
  - Too much causes additional, unnecessary delays
  - Too little and expensive airborne delays may occur

- When should the GDP be created?
  - Waiting means that flights depart and cannot be delayed
  - Additional, improved capacity information becomes available over time

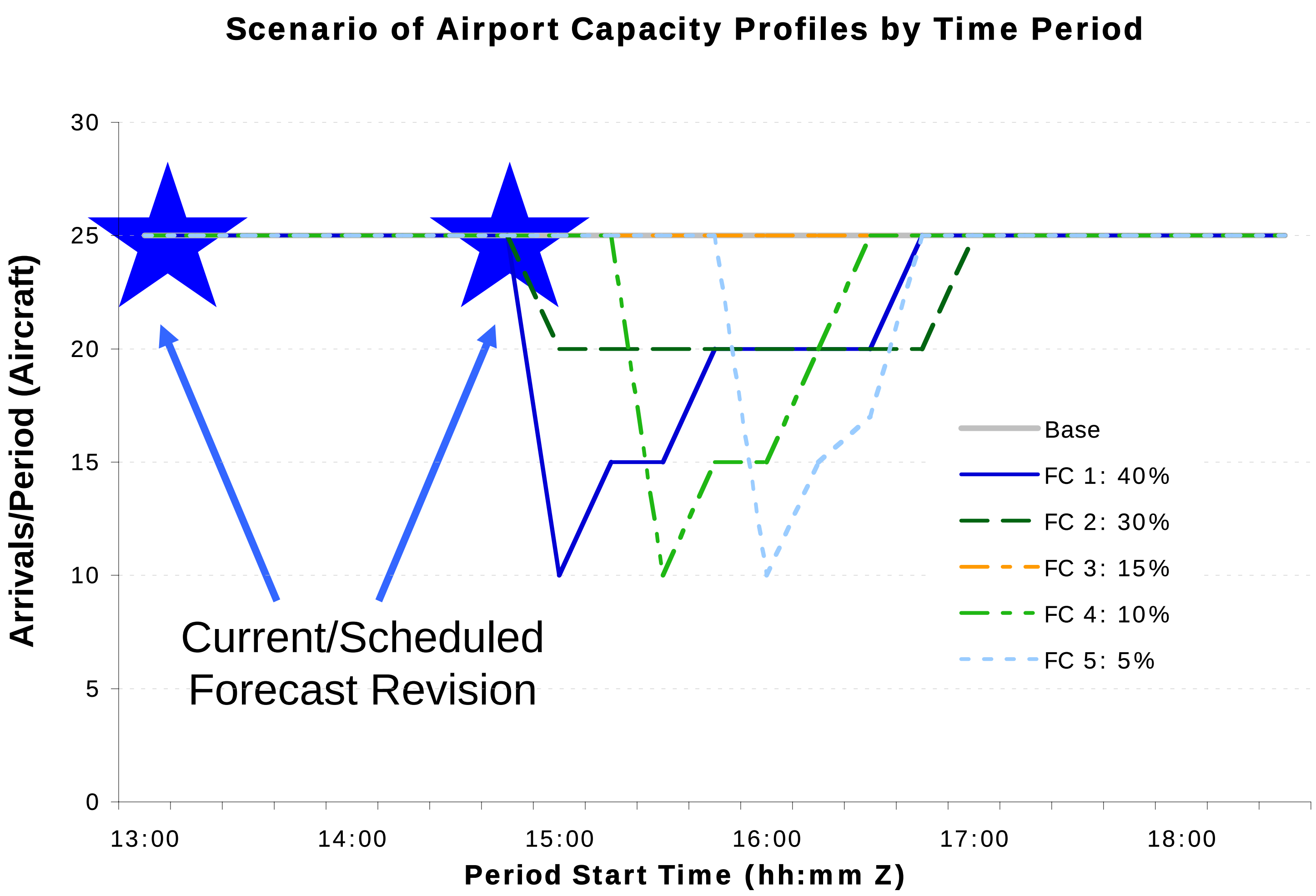
GDPs are both stochastic and dynamic

A numerical example: arrival demand over time



Source: ETMS, June 22nd, 14:45 Z, aggregated by author

A numerical example: arrival capacity scenario



Full Odoni Richetta (1993) formulation

Minimize:

$$\sum_{q=1}^{Q} p_q \left\{ \sum_{k=1}^{K} \sum_{s=1}^{Q} \sum_{i=t_s+1}^{T} \sum_{j=i+1}^{T+1} C_g(k, j-i) \times \chi_{qksij} + c_a \sum_{i=1}^{T} W_{qi} \right\}$$

Subject to:

$$\chi_{sksij} = \chi_{s+1ksij} = \ldots = \chi_{Qksij} \quad \forall\, s = 1\ldots Q-1;\, i = t_s + 1\ldots T;\, i \le j \le T+1;\, q = 1\ldots Q;\, k = 1\ldots K$$

$$\sum_{j=i}^{T+1} \chi_{qksij} = N_{ksi} \quad \forall\, k = 1\ldots K;\, s = 1\ldots Q;\, i = t_s + 1\ldots T$$

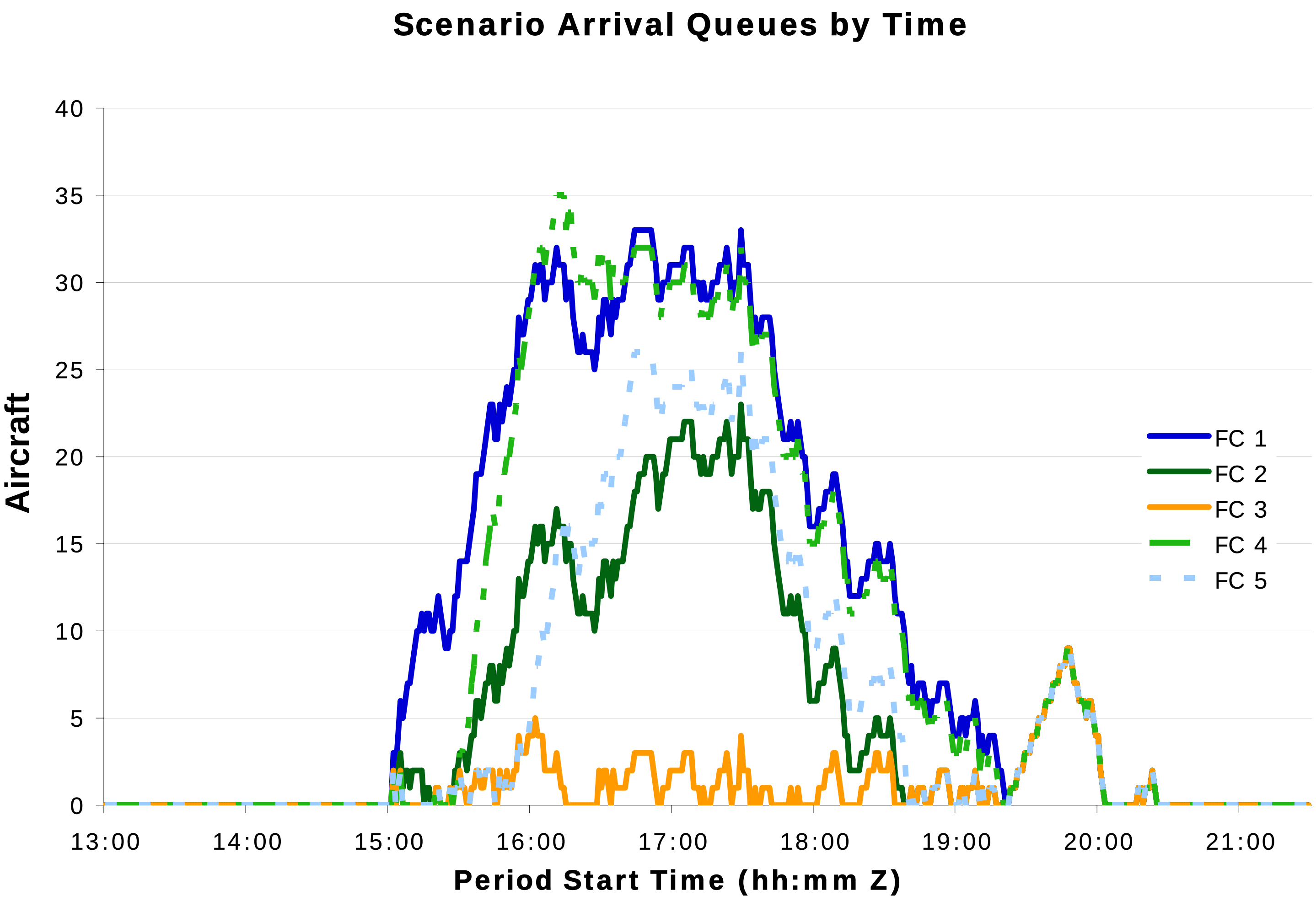
$$\sum_{i=1}^{T+1} S_{qi} = \sum_{i=1}^{T} M_{qi}$$

$$W_{qi} - W_{qi-1} - \sum_{k=1}^{K} \sum_{s:t_s<i} \sum_{j=t_s+1}^{i} \chi_{qksji} - S_{qi} = -M_{qi} \quad \forall\, i = 1\ldots T+1$$

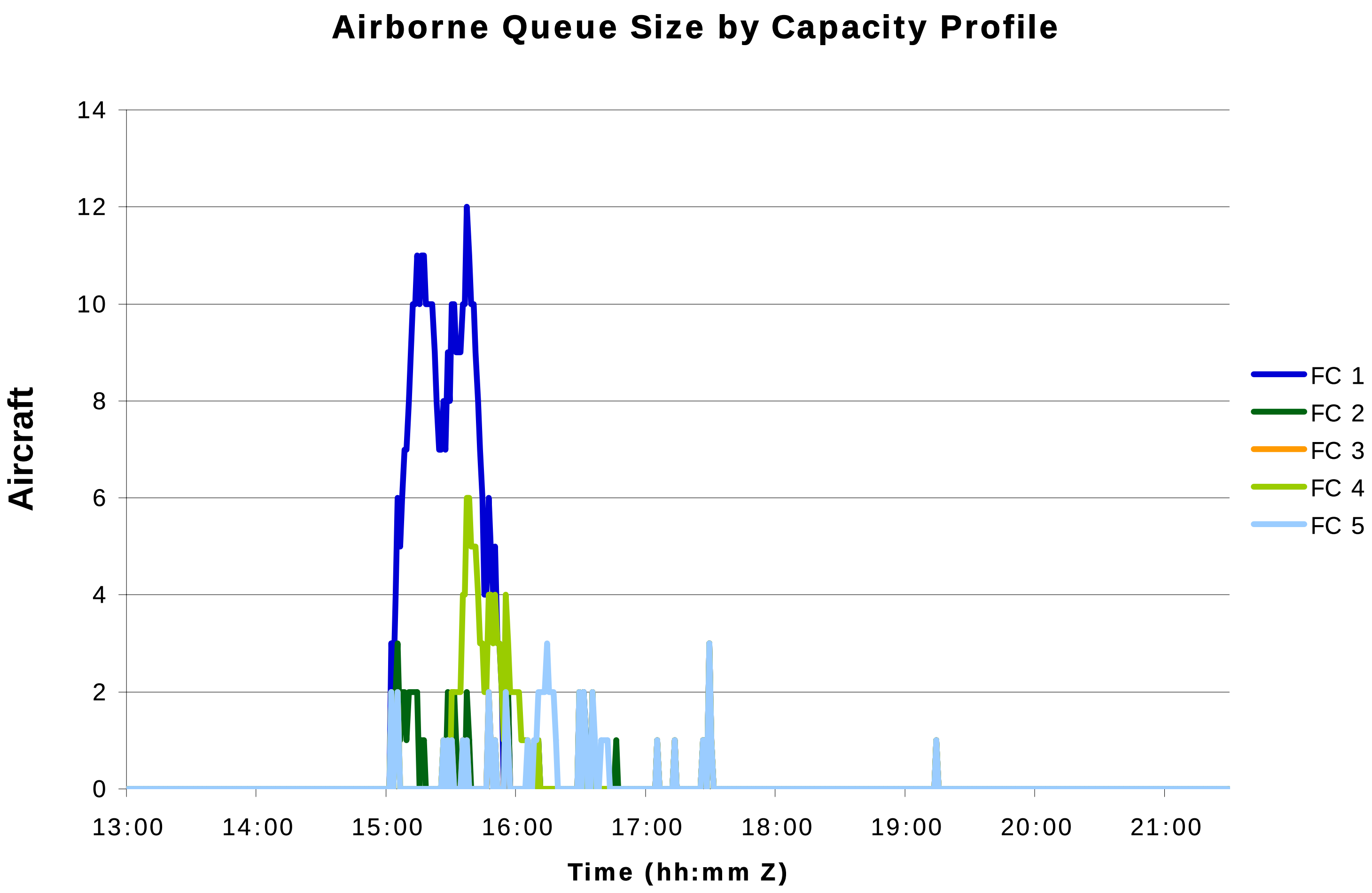
$$W_{q0} = W_{qT+1} = 0$$

$$\chi_{qksij}, W_{qi}, S_{qi} \ge 0$$

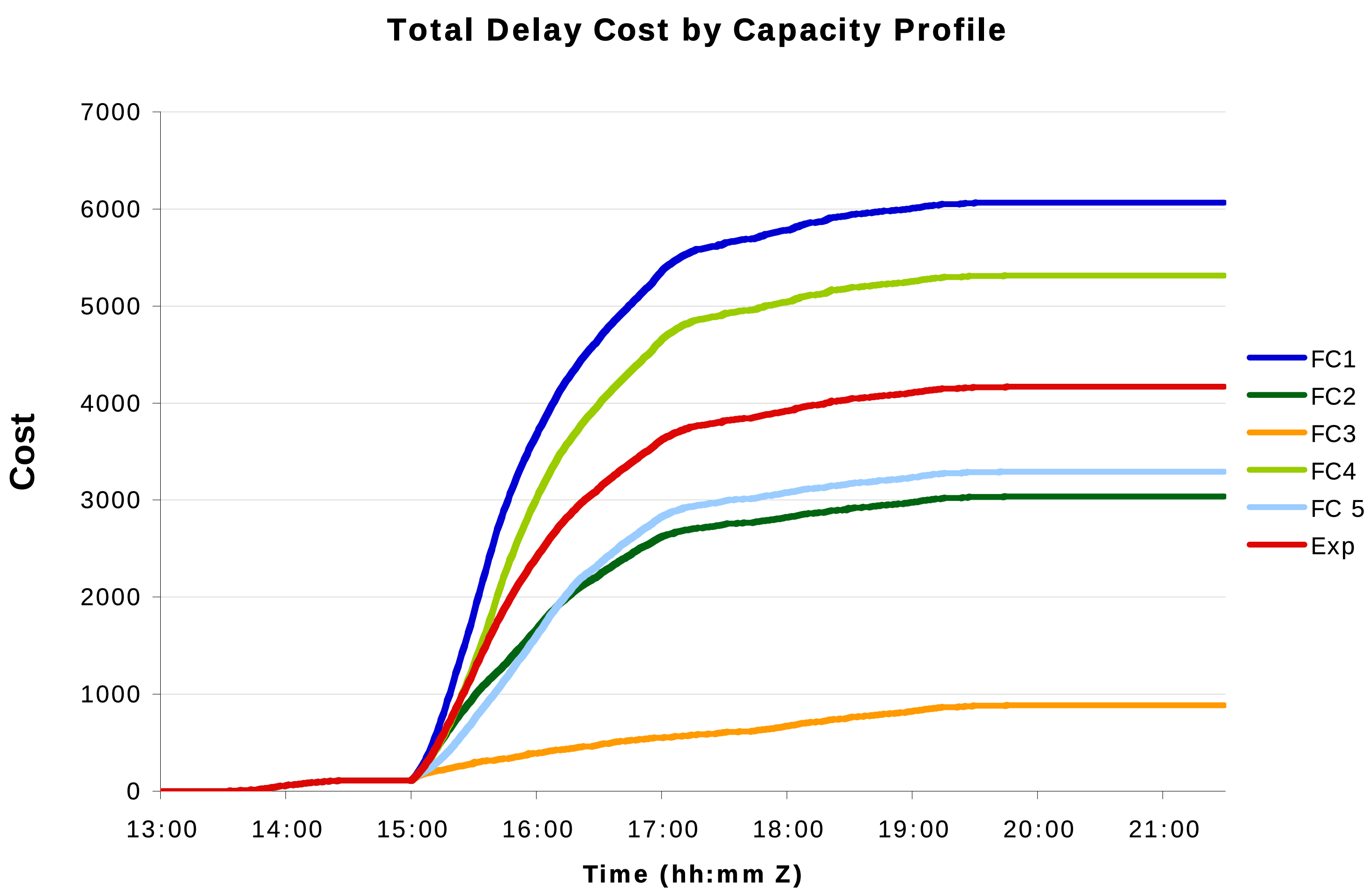
Queue Size – without a GDP



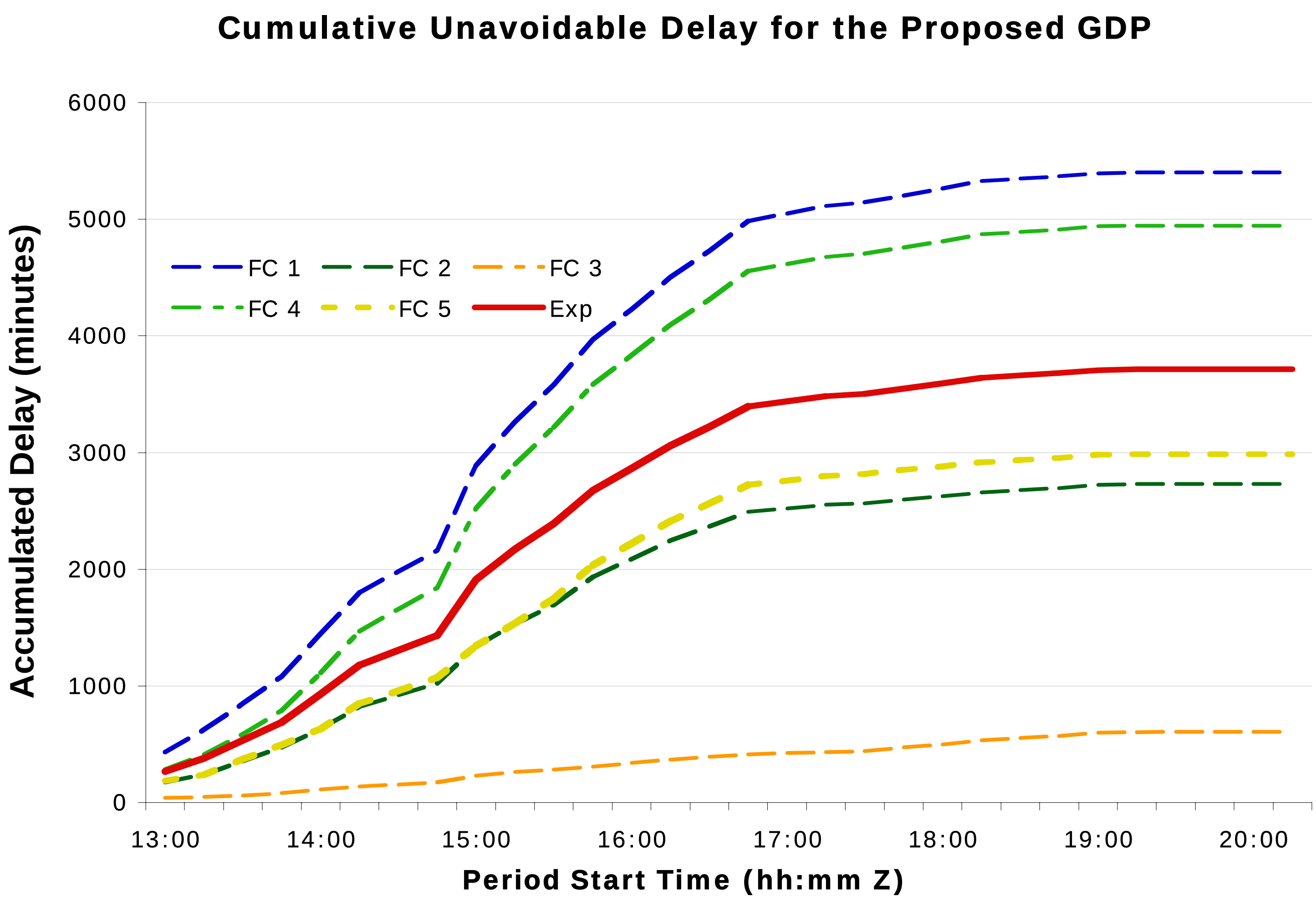
Queue Size – with the proposed GDP



Cumulative Delay Cost

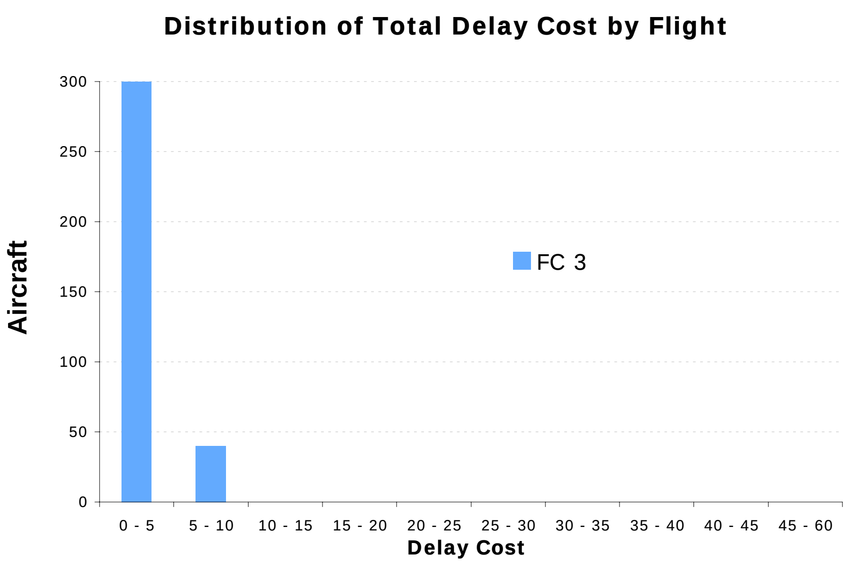


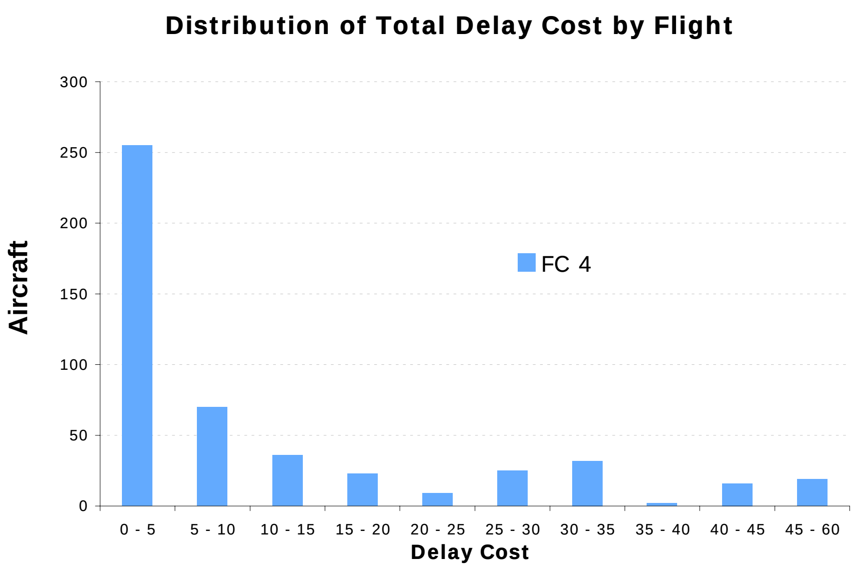
Unavoidable delay and critical decision times



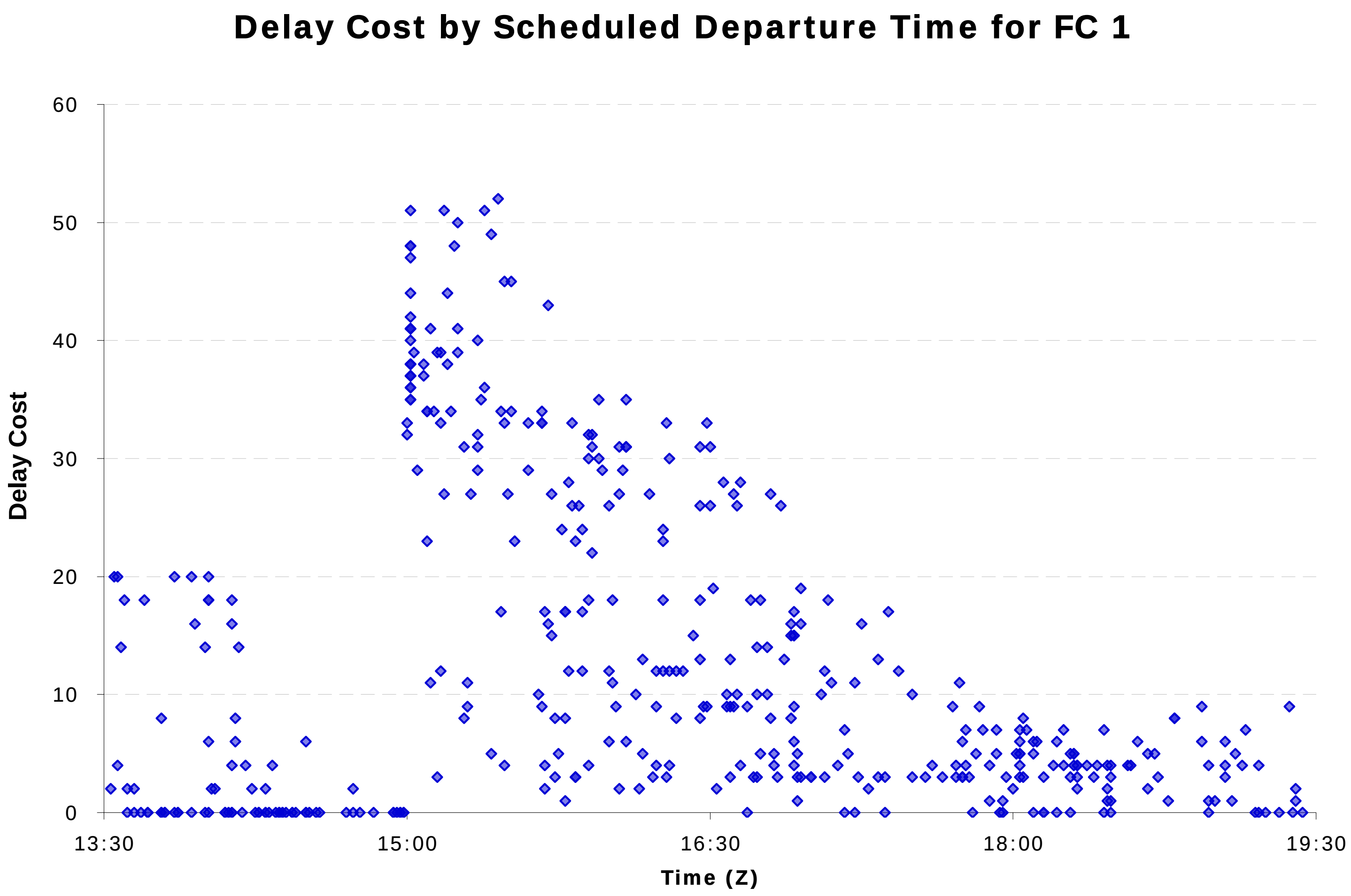
Flight delay distribution

- The distribution of delay cost will vary by outcome
  - FC 3 has a tight distribution
  - FC 4 assigns heavy delay costs to some flights
  - But… delay cost, as with demand and capacity, should vary

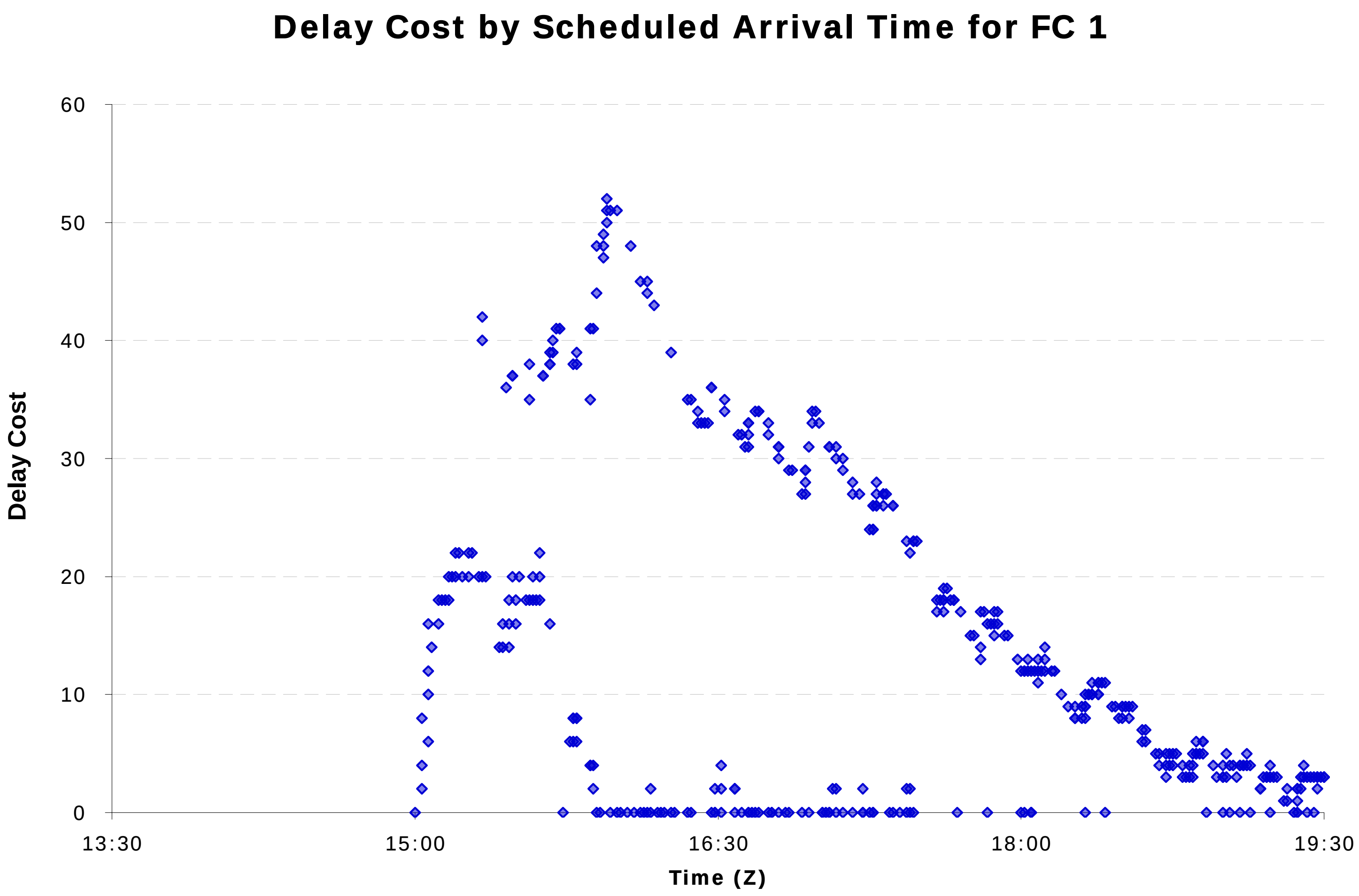




Flight delay by scheduled departure time



Flight delay by scheduled arrival time



Conclusions

- Optimization can be used to design GDPs
  - Offers an opportunity to improve the program
- Optimization techniques, however, are not the complete answer
  - Solutions do not consider important elements such as equity
  - Cannot guarantee many external constraints
  - May allow for the possibility of extreme outcomes
- It is important to have additional information
  - Other decision support tools can evaluate the proposed GDP
  - Optimization can be used as part of a larger process

Further research

- Improve decision-making process
  - Design LPs to address system loads
  - Design decision support tools and a process to incorporate them
- Define GDP design objectives
  - Cost functions should allow non-linear / aggregate delay costs
  - Equity should be defined within the GDP context
- Improve system modeling
  - Account for stochastic, dynamic demand
  - Model operator behavior for popups and cancellations
  - Further information from capacity profiles?

Methodology

- The design of a GDP must be approached from both a social and a technical perspective
- Improve understanding of the system
  - How decisions are made
    - Interview traffic managers at the FAA
  - How stakeholders are affected
    - Interview operation managers at different airlines

- Reformulate a model to capture new elements
- Define the role that optimization/models have in the overall GDP design process

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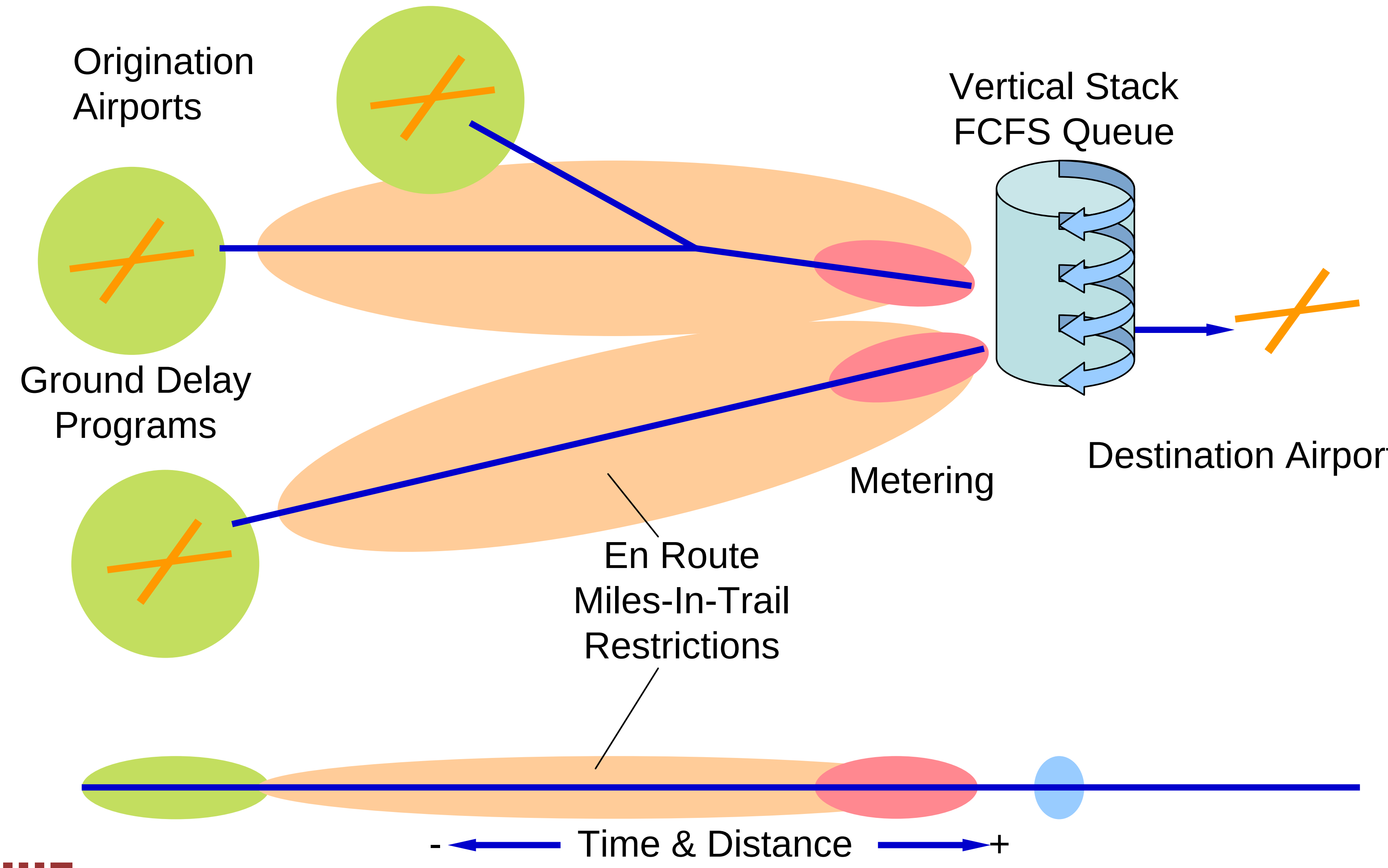
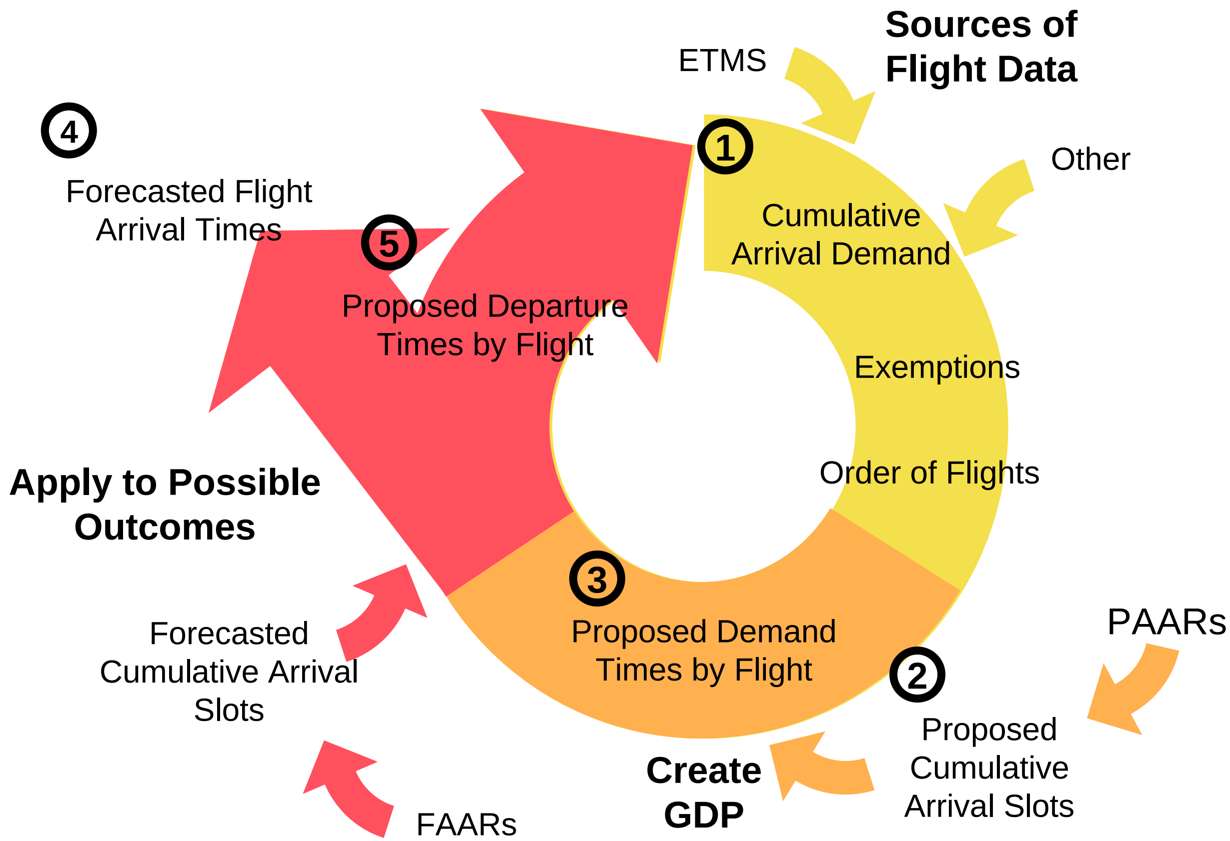
Appendix Table

- Key assumptions
- Stages/scenario clarification
- 1993 Odoni-Richetta formulation
- 2005 Mukherjee formulation
- Processing LP output into revised departure times
- Data calculation in the Hanowsky tool
- Different ATFM techniques
- Map of ARTCC boundaries
- Time and information tradeoff
- Categorization of sources of delay
- Relative ground/air cost functions
- Actual ground/air cost functions
- Relevant flight times

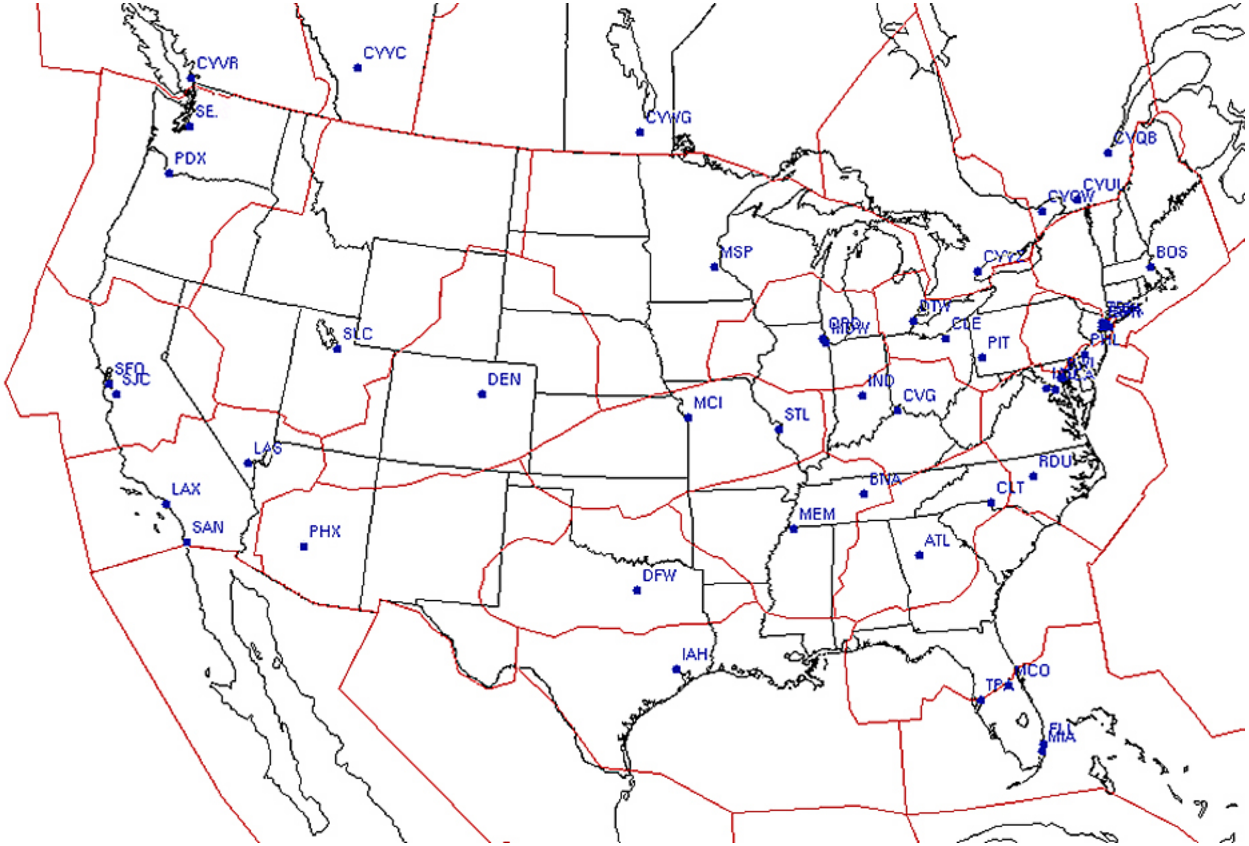
Ground Delay Programs require more advance planning than other ATFM tools



Calculation and data flows in the Excel tool

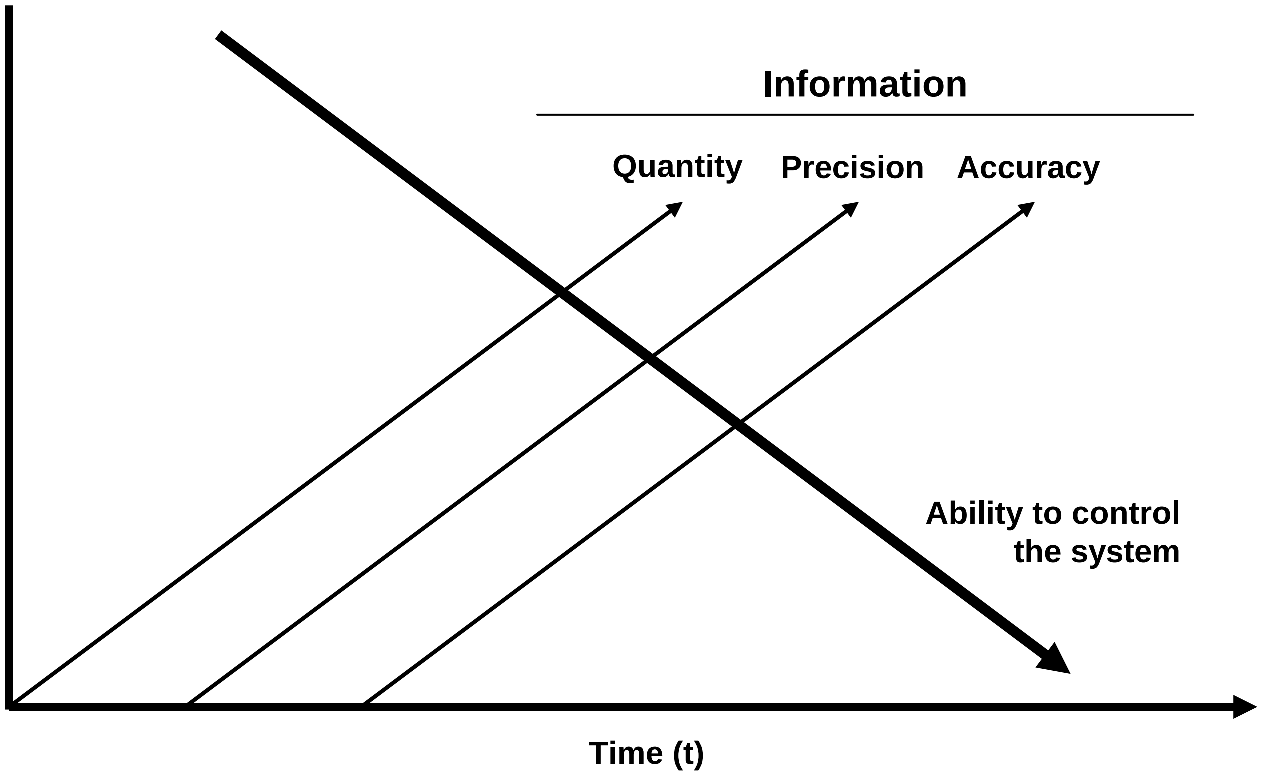


Map of the US with standard ARTCC boundaries

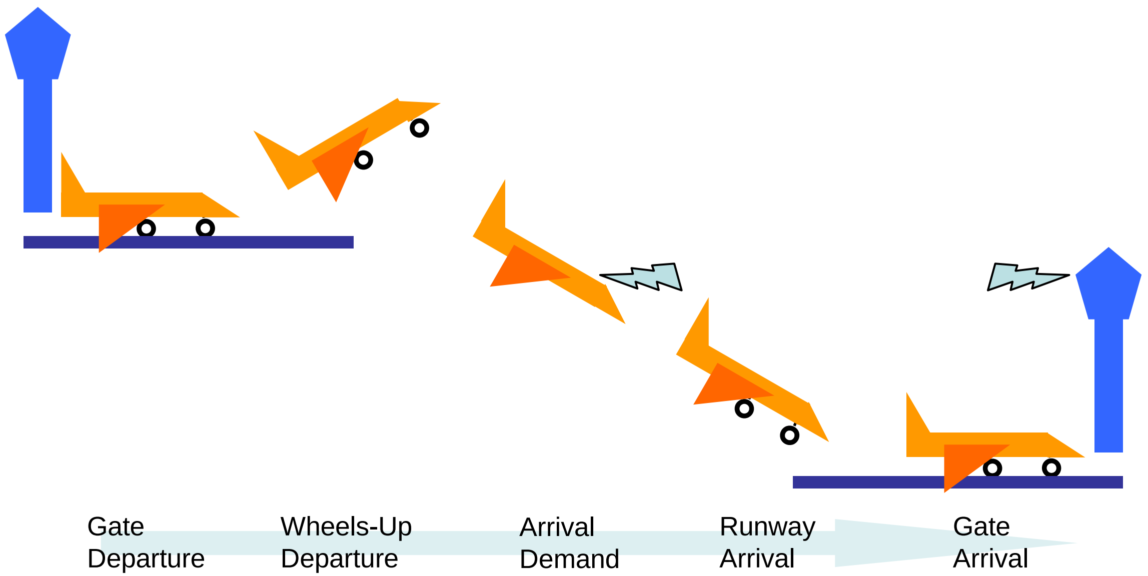


Source: Traffic Situation Display software (FAA), edited by the author using Adobe Photoshop

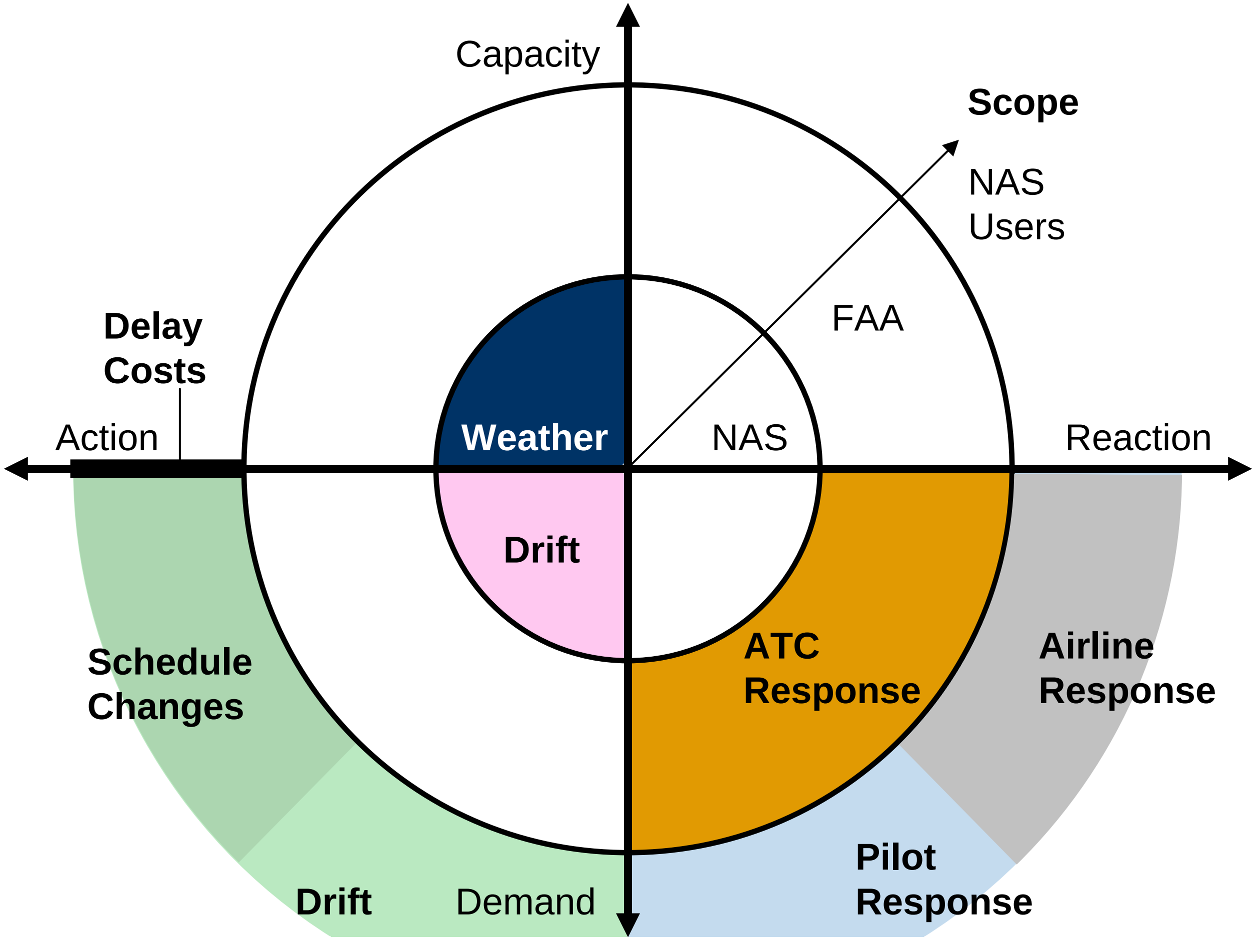
The relationship between time and information



Flight times relevant to ETMS arrival demand forecasts



Categorization of delay sources



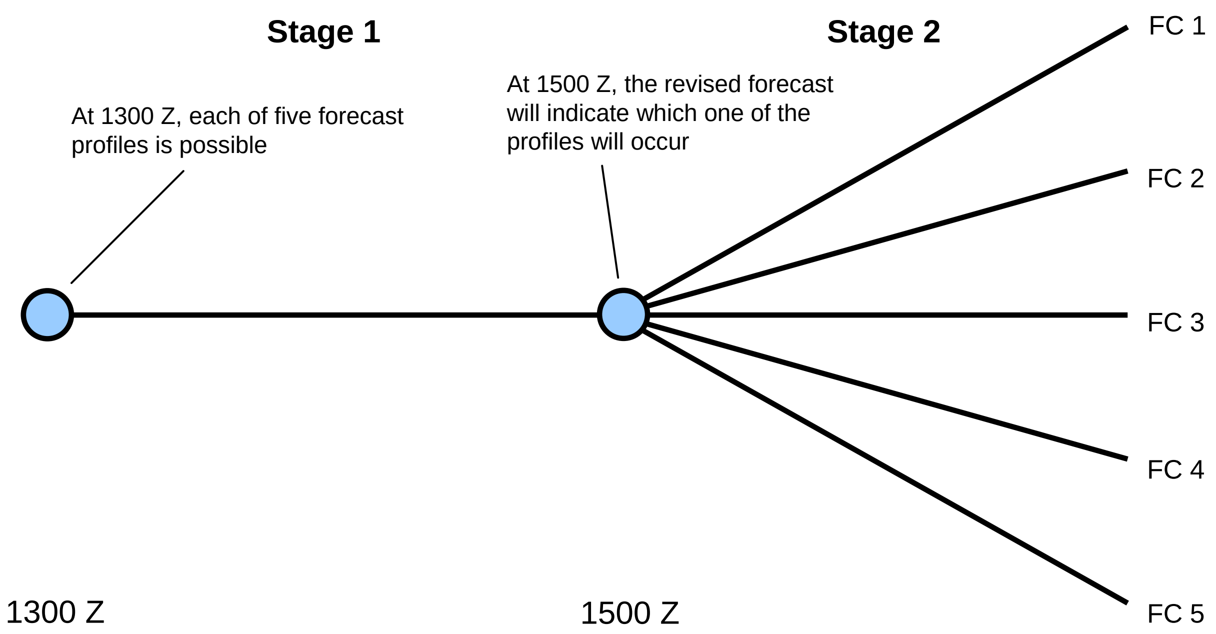
Recent Literature: There is an opportunity

- Uncertain forecast arrival capacities can be quantified
  - MIT Lincoln Laboratory (2004): use airport-specific meteorological data
  - Hansen and Liu (2006): use historical AARs
- Linear programming techniques can model GDPs with uncertain arrival capacities
  - Odoni and Richetta (1993): stochastic and dynamic conditions
  - Mukherjee and Hansen (2004): aircraft based model
- GDPs with uncertain arrival capacities can be analyzed
  - Hanowsky (2006): Analysis of GDPs with uncertain capacity

Existing literature does not discuss the application of optimization models

The system is dynamic

- Flight arrival demand changes
- Information on arrival capacity improves
  - Limited by the “two-stage” decision model



Odoni-Richetta (1993): 2 stages and 1 aircraft class

Minimize:

$$\sum_{q=1}^{Q} p_q \left\{ \sum_{s=1}^{2} \sum_{i=t_s+1}^{T} \sum_{j=i+1}^{T+1} C_g (j-i) \times \chi_{qsij} + C_a \sum_{i=1}^{T} W_{qi} \right\}$$

Minimize Cost

Subject to:

$$\chi_{11ij} = \chi_{21ij} = \ldots = \chi_{Q1ij} \;\; \forall \; i = t_s + 1 \ldots T; \; i \le j \le T+1$$

Solve each decision

$$\sum_{j=i}^{T+1} \chi_{qsij} = N_{si} \; \forall s = 1 \ldots 2; \; i = t_s + 1 \ldots T; \; q = 1 \ldots Q$$

$$\sum_{i=1}^{T+1} S_{qi} = \sum_{i=1}^{T} M_{qi} \;\; \forall \; q = 1 \ldots Q$$

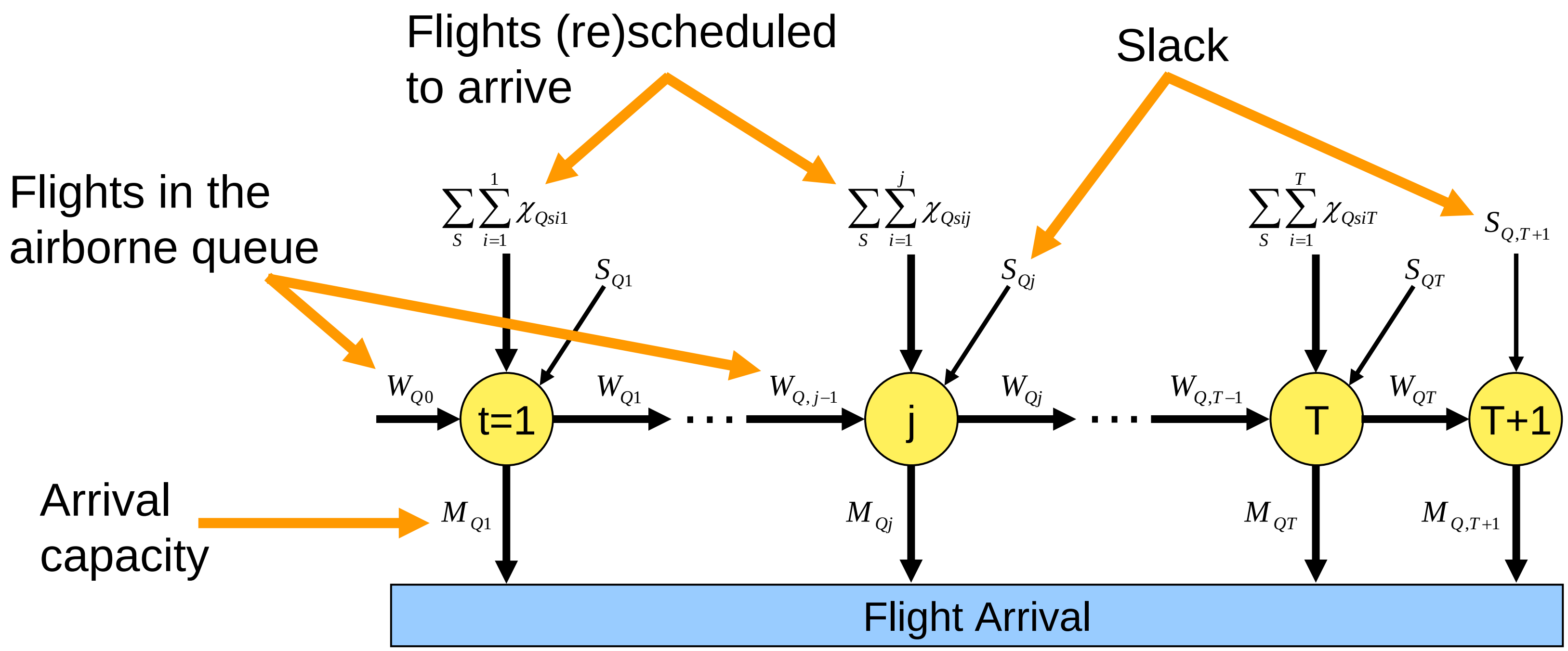
Conserve Flow

$$M_{qj} + W_{qj} = W_{qj-1} + \sum_{s:t_s<j} \sum_{i=t_s+1}^{j} \chi_{qsij} + S_{qj} \;\; \forall \;\; j = 1 \ldots T+1; \; q = 1 \ldots Q$$

$$W_{q0} = W_{qT+1} = 0$$

$$\chi_{qsij}, W_{qi}, S_{qi} \ge 0$$

The formulation is an adapted network flow model



$$M_{qj} + W_{qj} = W_{qj-1} + \sum_{s:t_s<j} \sum_{i=t_s+1}^{j} \chi_{qsij} + S_{qj} \quad \forall\ j = 1 \ldots T+1;\ q = 1 \ldots Q$$

LP Results: Wait for more information

- Only limited delays are assigned to flights that depart before 1500 Z
  - 23 flights
  - 2 hours cumulative delay
    - Delays shown in h:mm
    - Aircraft operator codes have been masked
- Delay assigned to flights that depart after 1500 Z depends on the capacity of stage 2
- Objective function value
  - Two-Stage: 3,820 a/c-delay min
  - One-Stage at 1500 Z: 3,845 a/c-delay min
  - No GDP: 7,356 a/c delay min

Before 1500 Z	
Flight	**Delay**
10A321	0:01
01A1840	0:01
53A1214	0:26
10A727	0:21
53A534	0:02
01A1476	0:01
53A132	0:14
48A46	0:01
40A8083	0:01
53A1114	0:03
53A783	0:15
53A570	0:14
01A2332	0:02
53A8173	0:02
53A1144	0:04
44A800	0:02
53A8124	0:03
54A1825	0:06
01A2325	0:01
01A1311	0:02
09A1	0:02
48A128	0:01
46A908	0:01
Total	**2:06**

System Load

- Objective
  - FAA defines specific system load standards to ensure safety
    - Strict limits on the number of aircraft
      - in a sector
      - under the responsibility of one controller

- …and Subjective
  - Not always easy to predict whether a future time/location will meet this standard
    - Flight location, speed uncertain
    - The FAA can apply other techniques to reduce demand

Efficiency

- Efficiency
  - Maximization of use of system, minimize “cost”
  - Scarce resources:
    - Fuel
    - Time
    - Airspace
- LPs can maximize an objective function

  …but can an appropriate objective function be identified?

Equity

- Very subjective

- Define equity by how the FAA views the system
  - All aircraft are treated independently and identically
  - Aircraft size, economy, passenger load… *not* considered

Do GDPs assign delays to some flights more than others?

Do GDPs assign more delays to some carriers than others?

- There are many other ways to define equity
  - Passengers, system efficiency

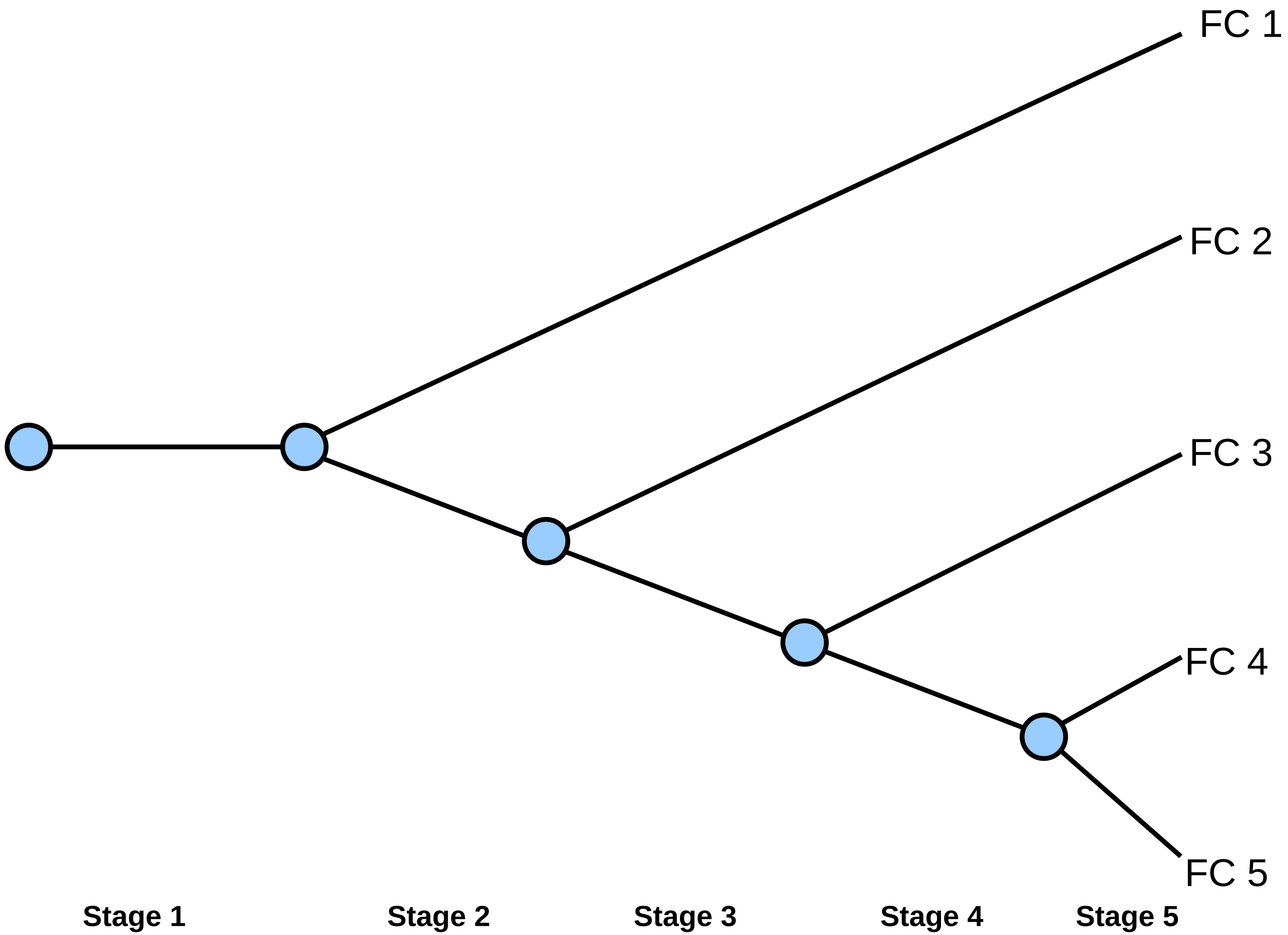
Key Assumptions

- En route times are deterministic and constant
  - Drift, en route congestion, other ATFM strategies
- Demand is constant
  - Popups, cancellations
- Flight arrival order is processed as a single FCFS D/D/1 queuing system
  - Multiple runway system, tactical ATFM
- Air carriers will adhere to assigned departure times
  - NavCanada

Subjective Criteria

- GDPs are designed by traffic managers at the FAA
  - A framework is used to guide decisions
  - No optimization tools are used
- “Safe and efficient”
- Equitable
  - Idea: Are programs sustainable?
  - Do users receive more benefits than costs?

Example of stages/scenarios



Full Odoni Richetta (1993) formulation

Minimize:

$$\sum_{q=1}^{Q} p_q \left\{ \sum_{k=1}^{K} \sum_{s=1}^{Q} \sum_{i=t_s+1}^{T} \sum_{j=i+1}^{T+1} C_g(k, j-i) \times \chi_{qksij} + c_a \sum_{i=1}^{T} W_{qi} \right\}$$

Subject to:

$$\chi_{sksij} = \chi_{s+1ksij} = \ldots = \chi_{Qksij} \quad \forall\ s = 1 \ldots Q-1; i = t_s + 1 \ldots T; i \le j \le T+1; q = 1 \ldots Q; k = 1 \ldots K$$

$$\sum_{j=i}^{T+1} \chi_{qksij} = N_{ksi} \quad \forall\ k = 1 \ldots K; s = 1 \ldots Q; i = t_s + 1 \ldots T$$

$$\sum_{i=1}^{T+1} S_{qi} = \sum_{i=1}^{T} M_{qi}$$

$$W_{qi} - W_{qi-1} - \sum_{k=1}^{K} \sum_{s:t_s<i} \sum_{j=t_s+1}^{i} \chi_{qksji} - S_{qi} = -M_{qi} \quad \forall\ i = 1 \ldots T+1$$

$$W_{q0} = W_{qT+1} = 0$$

$$\chi_{qksij}, W_{qi}, S_{qi} \ge 0$$

Avijit Mukherjee (2005) formulation (UC Berkeley PhD Thesis)

Minimize:
$$\sum_{q\in\Theta} P(q)\times\left\{\left[\sum_{f\in\Phi}\sum_{t=Arr_f}^{T+1}\left(t-Arr_f\right)\times\left(\chi_{f,t}^{q}-\chi_{f,t-1}^{q}\right)\right]+\lambda\times\sum_{t=1}^{T} w_t^q\right\}$$

Subject To:
$$\chi_{f,t}^{q}-\chi_{f,t-1}^{q}\geq 0$$
$$w_{t-1}^{q}-w_t^q+\sum_{f\in\Phi}\left(\chi_{f,t}^{q}-\chi_{f,t-1}^{q}\right)\leq M_t^q$$
$$w_0^q=w_{T+1}^q=0$$
$$\chi_{f,T+1}^{q}=1$$
$$Y_{f,t}^{S_1^i}=Y_{f,t}^{S_k^i}=Y_{f,t}^{S_{N_i}^i}\quad \forall\ f\in\Phi;\ t\in\{1\ldots T\};\ S_k^i\in\Omega_i : N_i\geq 2,\ \sigma_i\leq t\leq\mu_i$$

Delay assignment (based on the Odoni-Richetta formulation)

- Ground delays are assigned based upon underlying FAA methodology: FCFS by aircraft
  - Consider five flights in stage 1 (13:00 to 15:00) with arrivals between 15:00 Z and 15:04 Z.
  - LP output: $\chi_{25,25} = 3$ and $\chi_{25,27} = 2$

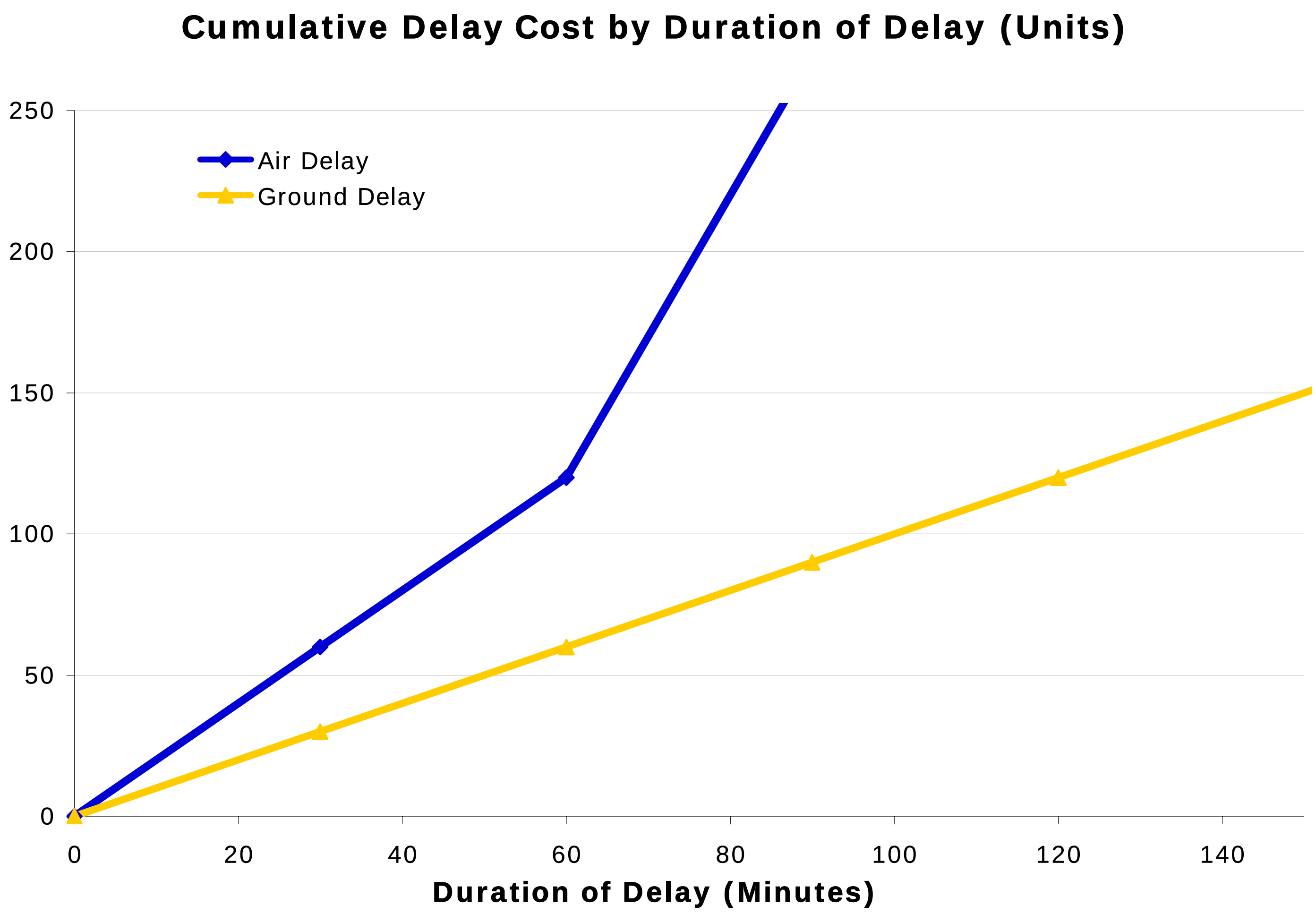
Flight	Dep Time	Arr Time
A1	14:00 Z	15:00 Z
A2	14:22 Z	15:01 Z
A3	13:00 Z	15:02 Z
A4	13:45 Z	15:03 Z
A5	13:00 Z	15:04 Z

Flight	Rev Arr	Rev Dep
A1	15:00 Z	14:00 Z
A2	15:01 Z	14:22 Z
A3	15:02 Z	13:00 Z
A4	15:10 Z	13:52 Z
A5	15:10 Z	13:06 Z

Gnd Delay
0:00
0:00
0:00
0:07
0:06

  - Arrival times are assigned FCFS
  - For delayed flights, the revised arrival times are at the beginning of the new arrival period
  - En route time is assumed to be constant

One possible set of ground and air cost functions



Air, ground, and total cost functions