Air Traffic Flow Management at Airports: A Unified Optimization Approach

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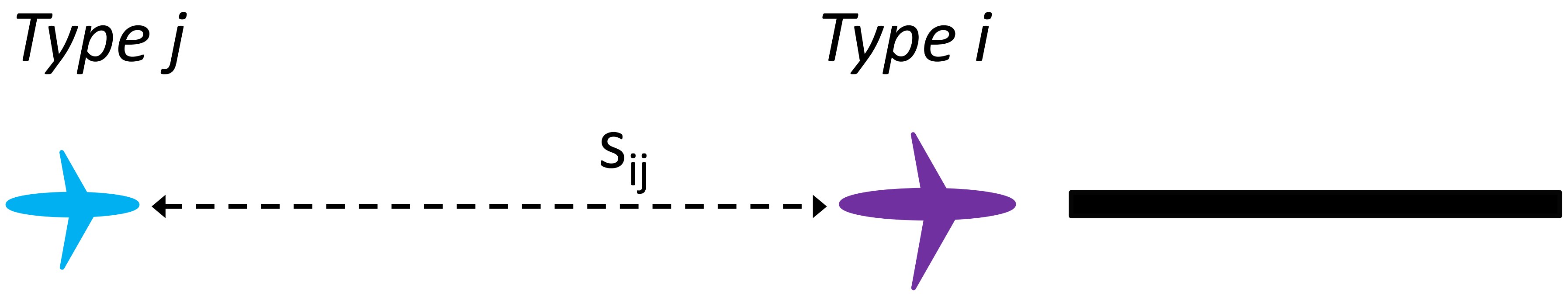
Motivation for *Unified Airport* Optimization

- Airports = key bottlenecks
- Current approaches in general solve sub-problems in isolation
  - Sub-optimality
  - Overall infeasibility

$\Rightarrow$ *Unified Approach*

Key Sub-problems at Airports

Runway Sequencing



- Minimum separation between flights
- Depends on flight *types*
  - Arrival, departure; heavy, B-757, large, small

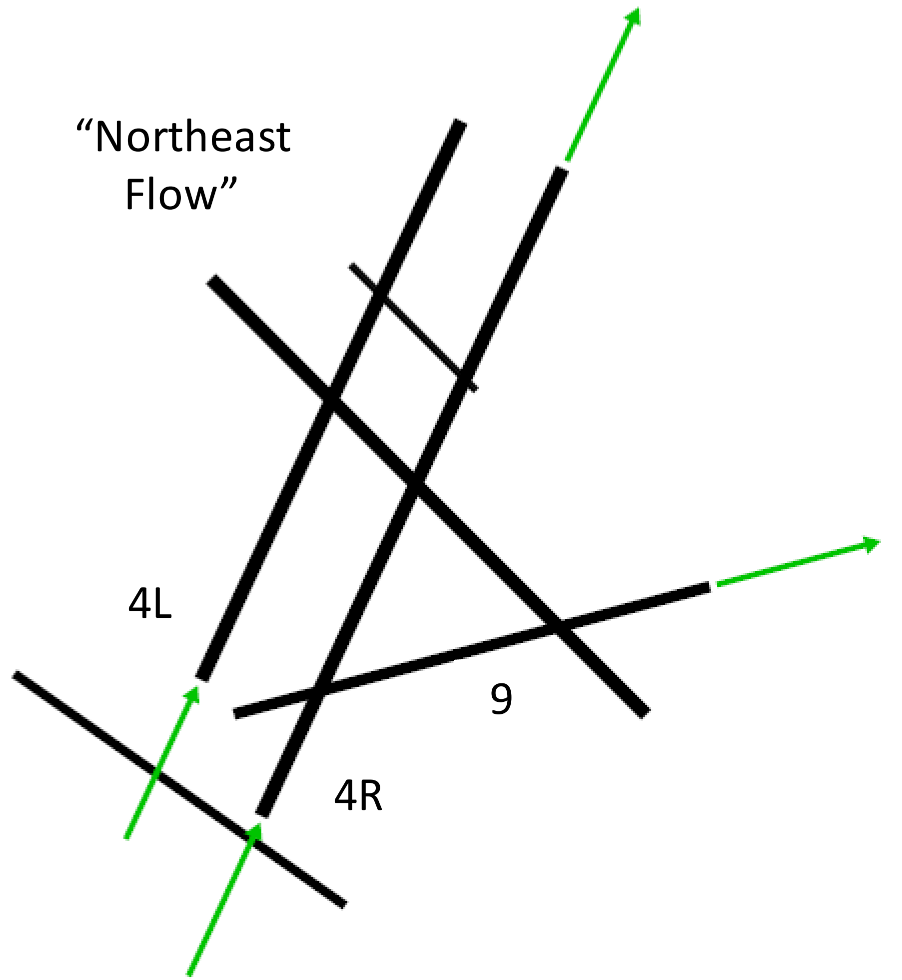
Runway Sequencing – Literature

- TSP/TRP
- Single runway
- Constrained position shifting
- Dynamic programming
- Time windows, side constraints
- Stochastic runway scheduling

- Dear (1976)
- Psaraftis (1980)
- Trivizas (1987)
- Balakrishnan and Chandran (2010)
- Clare and Richards (2011)
- Sölveling et al. (2011)

Runway Configuration Management

- Rules regulating runway use
- *Runway configuration =*
  - Combination of runways
  - Operating modes
- Which configuration?
- When?
- Literature:
  - Bertsimas, Frankovich, and Odoni (2011)



Flight Routing

- Route flights to assigned runway and beyond
- Determine gate-holding/speed control, if any

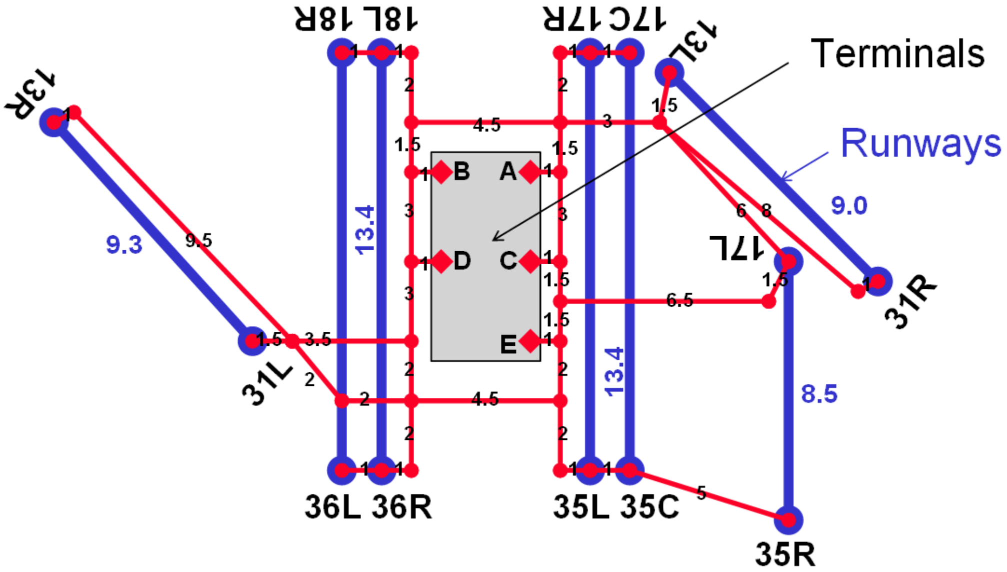


*Diagram thanks to Dr Tom Reynolds

Flight Routing – Literature

- Surface management:
  - Feron et al. (1997), Pujet et al. (1999), Carr (2001), Burgain (2010), Simaiakis et al. (2011)
- Taxi route optimization:
  - Marín (2006), Rathinam et al. (2008), Roling and Visser (2008), Malik et al. (2010)
- Sequencing & taxiing:
  - Gotteland et al. (2009), Clare and Richards (2011)

Airport Operations Optimization Problem (AOOP)

- Selecting a runway configuration sequence
- Determining the service rate of arrivals and departures
- Assigning flight types to runways and determining their sequence

Phase I

- Determining the gate-holding duration of departures
- Routing flights to their assigned runway and onwards within the terminal area

Phase II

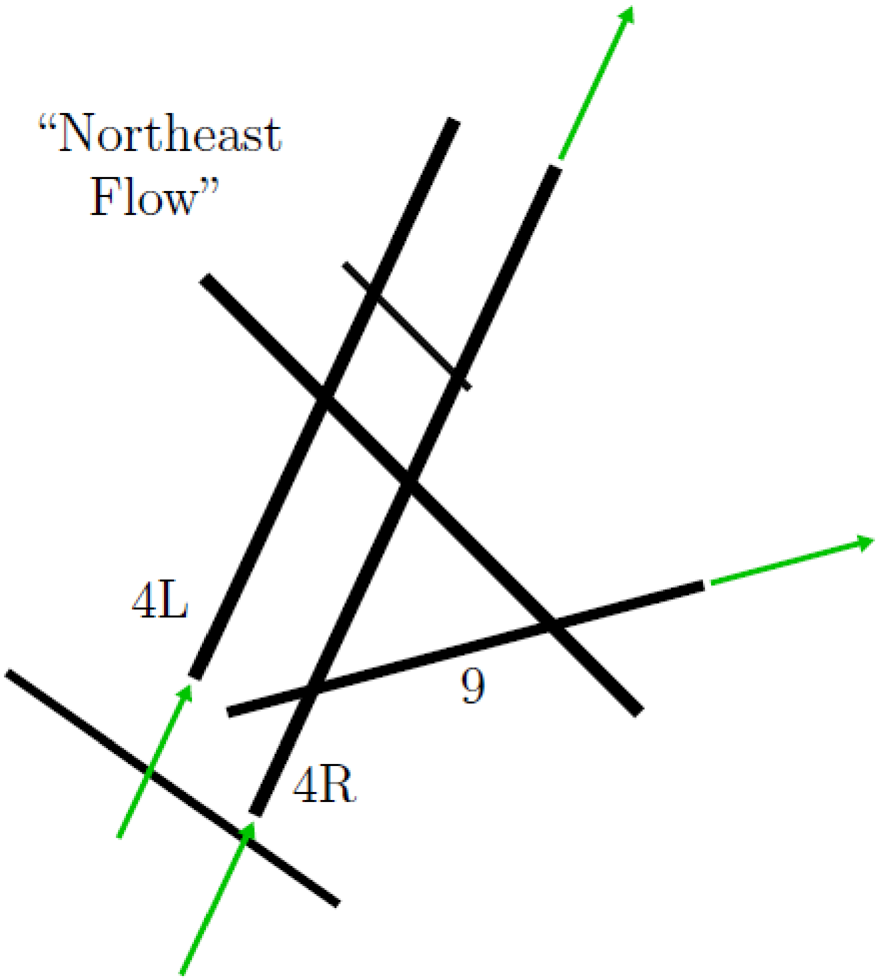
Summary of Approach

Two phases, each a binary optimization problem

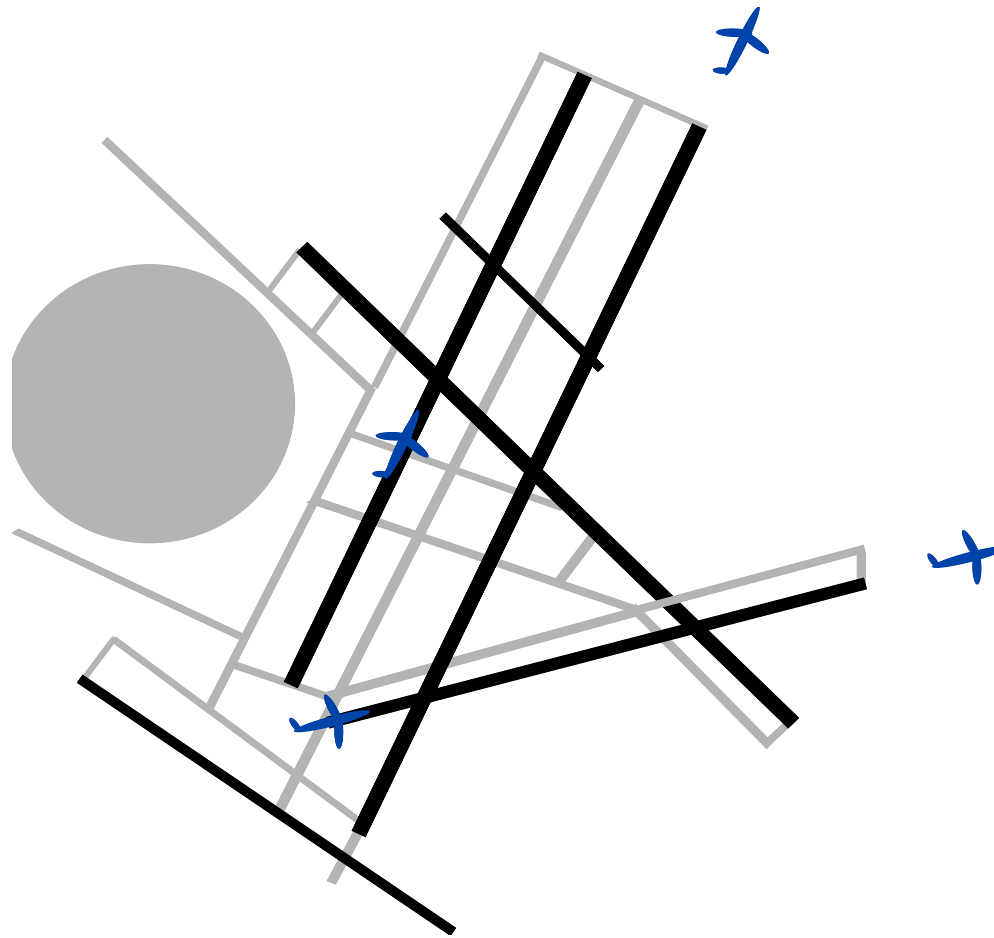
- Decomposition motivation:
  - key bottleneck of system at runways
  - so initially ignore capacity of gates, taxiways, airspace
- Phase I (Configurations, sequencing, assignment)
  - Optimal under assumption
- Phase II (Routing)
  - Uses phase one solution
  - Tractably solves AOOP without assumption

Phase I Decisions

Configuration Selection



Runway Assignment & Sequencing



Phase I – Key Data

- Time horizon 1,…T, @20s intervals
- Configuration availability U_t
- For each flight f:
  - A flight type i
  - Set of feasible runways R_f
  - For each runway r in R_f:
    - Earliest possible takeoff/landing time $\underline{T}^f_r$
    - Computed based on shortest paths
- Objective – weighted cost of delays

Phase I – Decision Variables

$\omega_{kt} = 1 \Leftrightarrow$ configuration k is used at time t

$\chi_t = 1 \Leftrightarrow$ we change configuration at time t

$\varphi^f_r = 1 \Leftrightarrow$ flight f is assigned to runway r

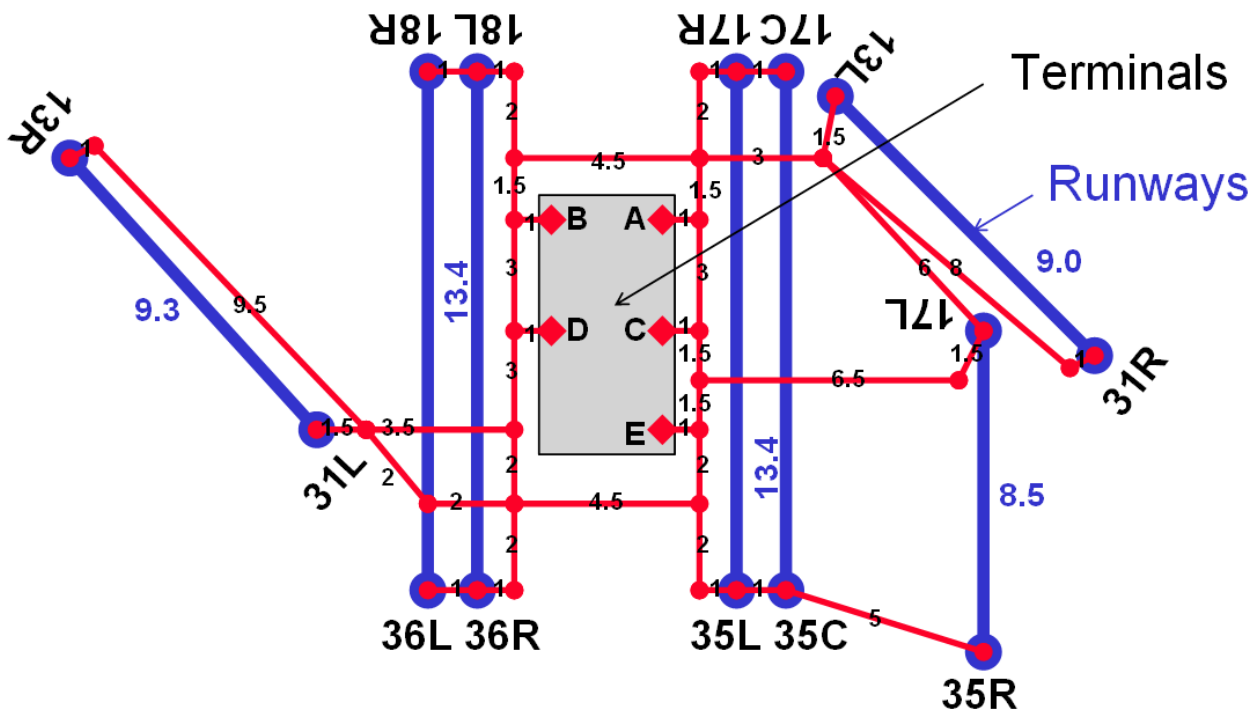
$\psi^i_{rt} = 1 \Leftrightarrow$ a flight of type i reaches runway r at t

- Naïve approach: ψ^f_{rt}
  - Separation constraints
  - Model size
- Flight-slot assignment guaranteed

$$
\begin{aligned}
\min \quad & \Psi \\
\text{s.t.} \quad & \sum_{k \in \mathcal{K}} \omega_{kt} = 1, \quad \forall t \in \mathcal{T}, && \text{(3.2a)} \\
& \psi^{i}_{rt} = 0, \quad \forall \boldsymbol{i} \in \mathcal{C},\ r \in \mathcal{U}_i,\ t \in \mathcal{T}, && \text{(3.2b)} \\
& \psi^{i}_{r,t-h} + \psi^{j}_{rt} \leq 1, \quad \forall \boldsymbol{i}, \boldsymbol{j} \in \mathcal{C},\ r \in \mathcal{R}_i \cap \mathcal{R}_j, \\
& \qquad h \in \{1, \dots, \min\{s^{r}_{ij} - 1, t - 1\}\},\ t \in \mathcal{T} \setminus \{1\}, && \text{(3.2c)} \\
& \psi^{i}_{r,t-h} + \psi^{j}_{r',t} \leq 1, \quad \forall \boldsymbol{i}, \boldsymbol{j} \in \mathcal{C},\ (r, r') \in (\mathcal{R}_i \times \mathcal{R}_j) \cap \mathcal{V}, \\
& \qquad h \in \{0, \dots, \min\{s^{(r,r')}_{ij} - 1, t - 1\}\},\ t \in \mathcal{T}, && \text{(3.2d)} \\
& \sum_{i \in \mathcal{C} : r \in \mathcal{R}_i} \psi^{i}_{rt} \leq 1, \quad \forall r \in \mathcal{R},\ t \in \mathcal{T}, && \text{(3.2e)} \\
& \psi^{i}_{rt} + \omega_{kt} \leq 1, \quad \forall t \in \mathcal{T},\ \boldsymbol{k} \in \mathcal{K},\ r \in \mathcal{R}_k,\ \boldsymbol{i} \in \bar{\mathcal{I}}_{rk} \ :\ r \in \mathcal{R}_i, && \text{(3.2f)} \\
& \psi^{i}_{rt} - \sum_{\substack{k \in \mathcal{K} : r \in \mathcal{R}_k, \\ i \in \mathcal{I}_{rk}}} \omega_{k,t+h} \leq 0, \quad \forall \boldsymbol{i} \in \mathcal{C},\ r \in \mathcal{R}_i, \\
& \qquad h \in \{0, \dots, \min\{l^{r}_{i} - 1, T - t\}\},\ t \in \mathcal{T}, && \text{(3.2g)} \\
& \sum_{r \in \mathcal{R}_f} \varphi^{f}_{r} = 1, \quad \forall f \in \mathcal{F}, && \text{(3.2h)} \\
& \sum_{\substack{f \in \mathcal{F}_i : r \in \mathcal{R}_f, \\ t \geq \overline{T}^{f}_{r} - l^{r}_{i} + 1}} \varphi^{f}_{r} \leq \sum_{\tau=1}^{t} \psi^{i}_{r\tau} \leq \sum_{\substack{f \in \mathcal{F}_i : r \in \mathcal{R}_f, \\ t \geq \underline{T}^{f}_{r}}} \varphi^{f}_{r}, \quad \forall \boldsymbol{i} \in \mathcal{C},\ r \in \mathcal{R}_i,\ t \in \mathcal{T}, \\
& && \text{(3.2i)} \\
& \chi_t - \omega_{kt} + \omega_{k,t-1} \geq 0, \quad \forall \boldsymbol{k} \in \mathcal{K},\ t \in \mathcal{T} \setminus \{1\}, && \text{(3.2j)}
\end{aligned}
$$

Phase II – The "Routing Phase"

Data:



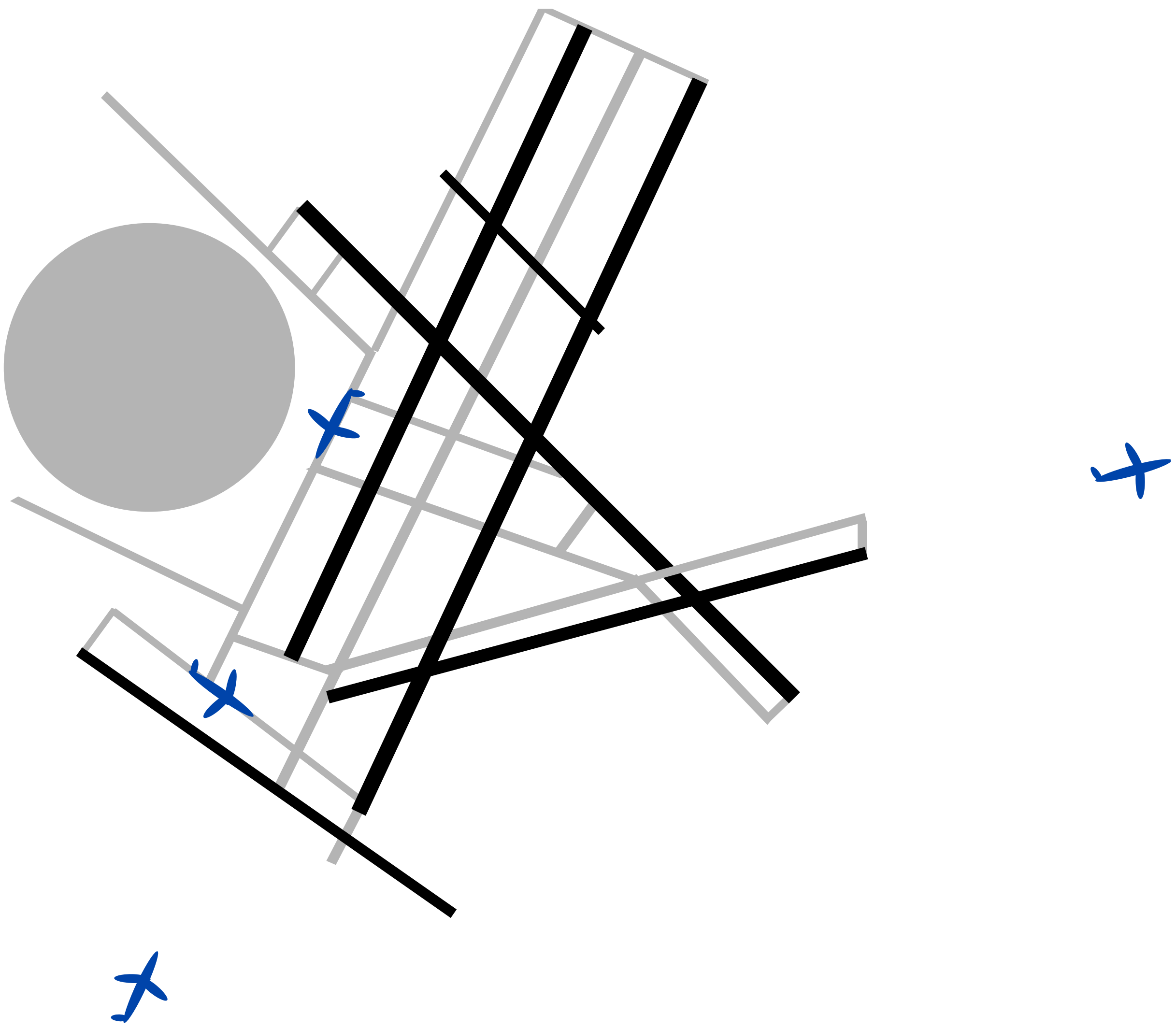
Key decision variables:

- $z^{f}_{jt} = 1 \Leftrightarrow$ flight f reaches node j *by* time t

Phase II – Summary

- Fix runway assignments and *sequences* from P1
- Ensure routing constraints met
  - Eg taxiway/runway crossings, etc
  - Fix separation
- If capacity sufficiently high, P1 solution optimal
  - flights processed at same time in P2 as P1
  - flights travel along shortest paths, unimpeded
- Else, runway times will differ slightly
  - here, need to ensure configurations respected
- Guaranteed feasible

Phase II Decisions - Routing



A Bound on the Optimality

- Phase II gives a feasible solution to AOOP
- An optimal solution to AOOP has value no better than the Phase I optimum
  - (It is the full problem, without routing constraints)
- This gives us a bound on the quality of our solution
- A large gap would indicate that the Phase I problem was far from feasible
  - Hence our assumption that runways key bottlenecks would be poor

Computational Experience – Aims

- Are our key assumptions valid?
- Is the methodology computationally tractable?
- Would the use of the methodology result in significant benefits in practice?

Computational Tractability & Bound on the Optimality Gap

Flights	Optimality Bound	Computational Times (s)		
		P1	***P2***	***Total***
155	2.1	120	1286*	1430
175	1.1	372	1071	1465
153	0.6	64	129	211
155	0.7	75	284	379
168	0.5	340	187	546
171	0.7	299	284	600
159	0.9	252	533	806

*=1% optimality gap

Using Data from DFW on 11/2/2009

Computational Tractability & Bound on the Optimality Gap

Flights	Optimality Bound	Computational Times (s)		
		P1	***P2***	***Total***
90	0.2	252	147	418
91	0.4	233	142	388
80	0.1	143	16	168
63	0.6	93	52	161
63	0.3	198	15	229
71	1.3	246	1200	1457
59	0.5	255	59	325

Using Data from BOS on 9/28/2010

Comparison of Optimized and Historic Surface Times

Optimized Surface Times (min./flight)				Historic Surface Times (min./flight)		
Dep. G.H.	***Dep.***	***Arr.***	***Avg.***	***Dep.***	***Arr.***	***Avg.***
1.8	9.5	10.8	10.2	13	8.9	10.7
2.2	9.2	10.7	9.9	12.8	9.3	11.2
1	9.5	10.6	10	13.5	9.2	11.6
1	9.6	11.1	10.4	13.5	9	11
0.9	9.3	11.8	10.5	13	10.1	11.6
2.1	10	11.4	10.7	13.6	8.9	11.3
1.3	9.1	10.8	10	13.9	9.1	11.4
0.7	9	11.1	10.1	13.4	9.6	11.2

Using data from DFW on 11/2/2009

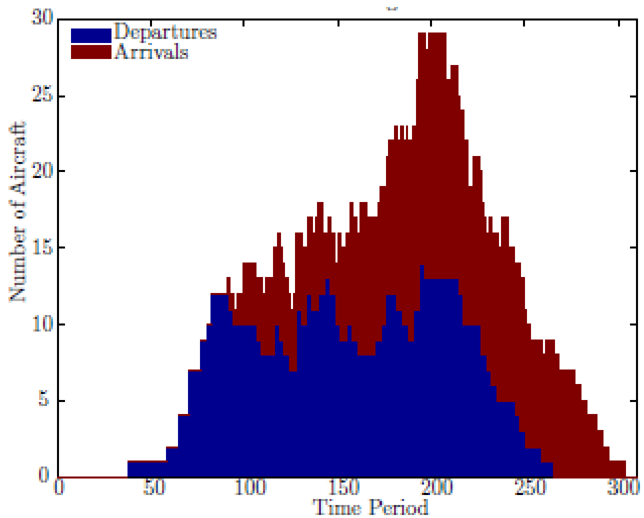
Comparison of Optimized and Historic Surface Times

Optimized Surface Times (min./flight)				Historic Surface Times (min./flight)		
Dep. G.H.	***Dep.***	***Arr.***	***Avg.***	***Dep.***	***Arr.***	***Avg.***
1.6	13.7	4.4	9.3	18.7	5.2	12.4
0.8	14	4.5	9.6	16.7	6.1	11.6
2.2	16.4	5	12.2	17.6	5.9	13.1
0.5	16.6	4.9	10.3	18.2	6.5	12.2
0.5	16	5	10.1	18.5	4.4	10.9
1.3	11.6	8.2	10.1	16.6	5.1	11.4
2.6	13.8	4.6	8.5	14.7	5.8	9.9
0.9	16.2	4.9	10.5	17.1	6.6	11.3

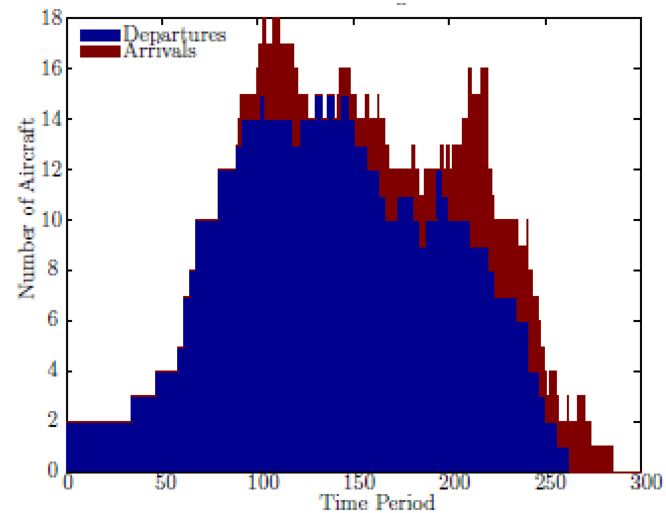
Using data from BOS on 9/28/2010

Surface Congestion

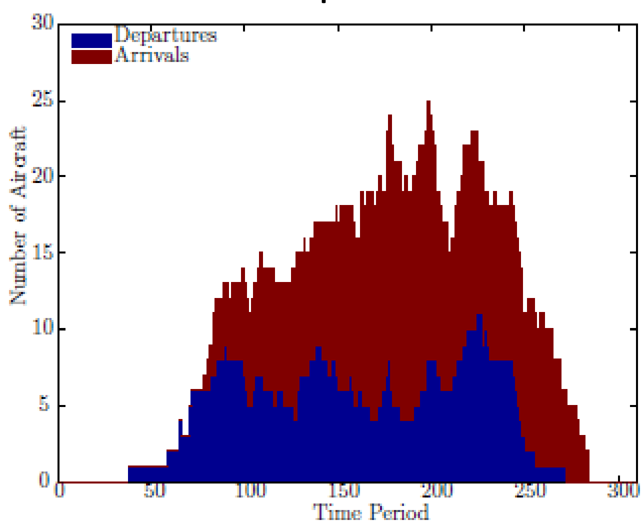
DFW Historic



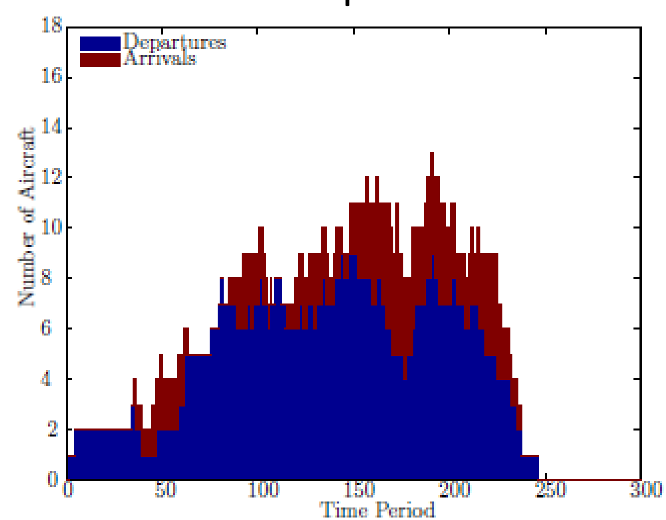
BOS Historic



DFW Optimized



BOS Optimized



Summary

- *Unified and tractable* approach to solve the entire Airport Operations Optimization Problem (AOOP)
  - Runway configuration management
  - Runway sequencing
  - Flight-runway assignment
  - Flight routing
  - Gate-holding

Limitations

- Who are the decision-makers?
  - Can we implement our solution?
- Uncertainty – see Frankovich (2012)
- Nevertheless:
  - Useful tool for measuring airport performance
  - Analysis of airport infrastructure changes

Thank You