Efficient and Equitable Departure Scheduling in Real-Time: New Approaches to Old Problems

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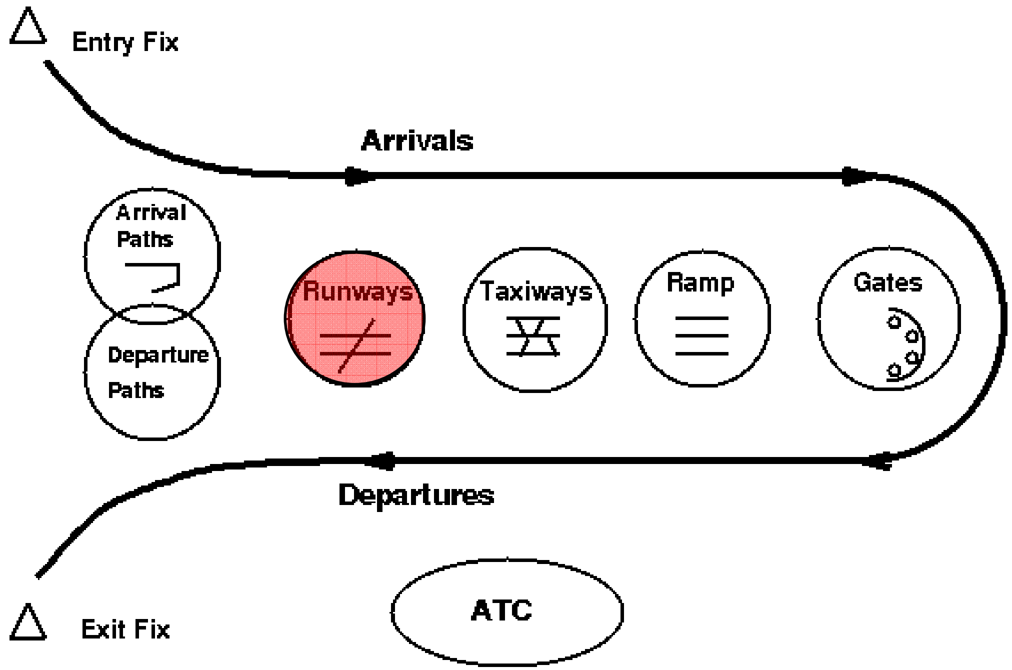
Motivation: Why schedule runways?

- The runway system is the key constraint in surface operations
- Critical interface between airport surface and airspace: runway operations strongly influenced by downstream constraints (departure flow management, departure fix closures, Ground Delay Programs)



[Idris et al. 2000, Carr 2004]

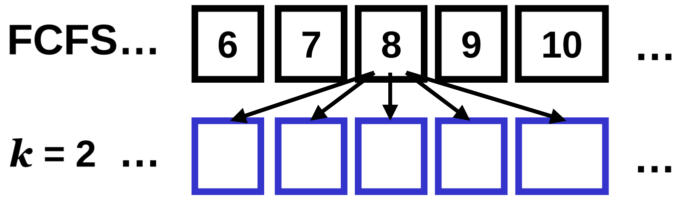
What is a “good” schedule?

- The real system has many operational constraints
  - ☐ Separation requirements for safety
  - ☐ Departure fix metering constraints
  - ☐ Traffic flow management requirements, etc.
  - ☐ Precedence constraints (“aircraft i must depart before aircraft j”) due to limited overtaking on taxiways, airline bank structures
- Runway schedules must satisfy operational constraints
- Equitable treatment of users (airlines)
- Several potential objective functions
  - ☐ Maximum throughput
  - ☐ Minimum average delay
  - ☐ Minimum sum of aircraft-dependent delay costs
  - ☐ Minimum (passenger)-weighted sum of delays
  - ☐ Minimum weighted sum of throughput and average delay

Equitable scheduling: Constrained Position Shifting

- Limits deviation from FCFS or some “nominal” sequence

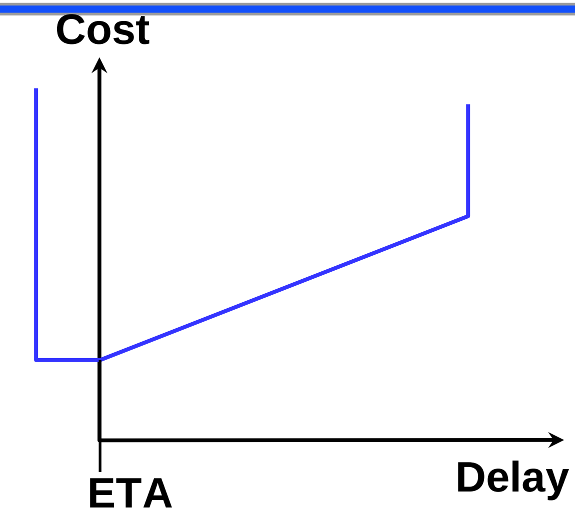
  Maximum number of position shifts, k (denoted k-CPS)



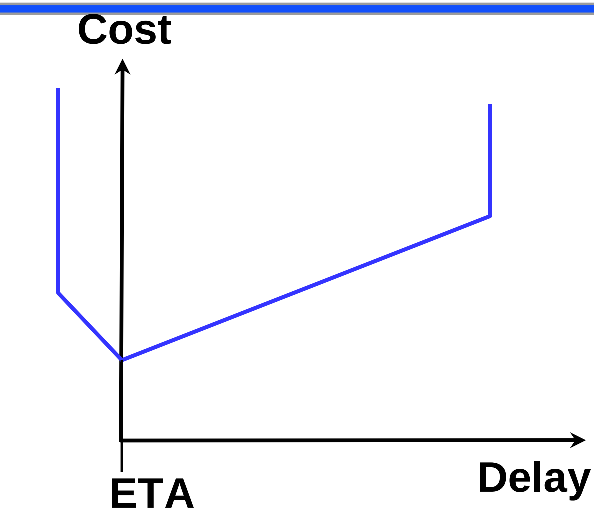
- Maintains a sense of fairness
  - ☐ Restricted deviation from a nominal or FCFS order
  - ☐ Airline perception of equity is maintained
- Easy to implement by controllers
  - ☐ Only small, local shifts in position ($k \leq 3$)

[Dear 1976, Psaraftis 1980, Neuman and Erzberger 1991, Venkatakrishnan, Barnett and Odoni 1993, Trivizas 1998, Carr 2004]

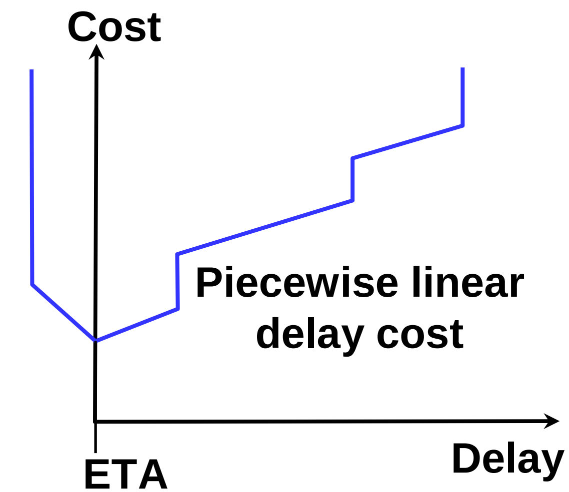
Efficiency: Many potential “delay costs”

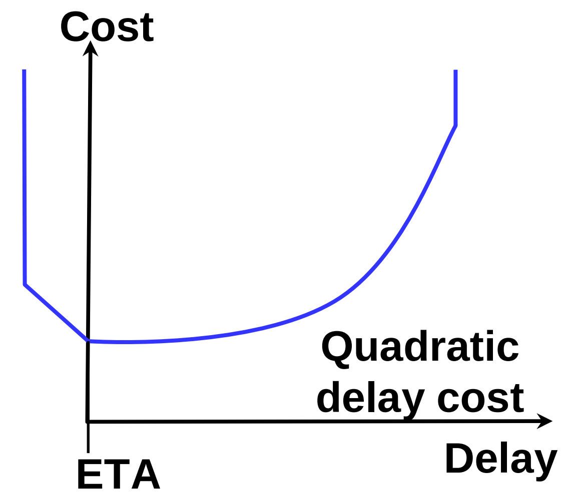


No penalty for speed up



Linear penalty for speed up





Approaches to departure scheduling

- Different solution approaches have been applied for different objective functions, including
  - Dynamic programming
  - Integer programming
  - Various heuristics

- Scheduling under Constrained Position Shifting (CPS) has been shown to have a solution space that is exponentially large in the number of aircraft in the sequence
  - Scheduling under CPS has been conjectured to have exponential computational complexity
  - **We have shown that this is not true!**

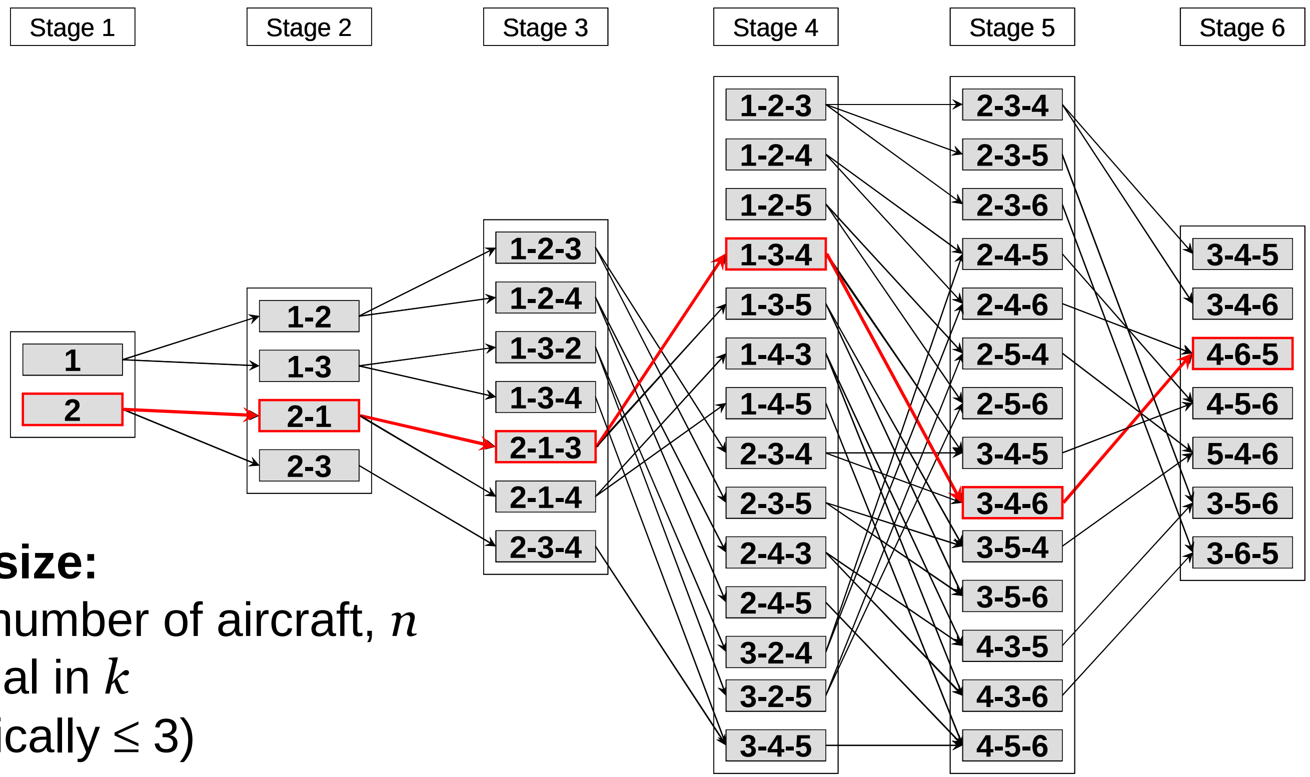
[Psaraftis 1980, Neuman and Erzberger 1991, Trivizas 1998, Beasley 2000, Anagnostakis 2001, Carr 2004]

A unifying framework for scheduling under CPS

- CPS constraints make the problem *easier* to solve by enabling an efficient representation of the solution space

- All possible sequences are represented as a path in a network

n = 6
k = 1



Network size:
Linear in number of aircraft, n
Exponential in k
(But k typically $\leq$ 3)

The k-CPS network

- Size (number of nodes and arcs) of the CPS network is linear in the number of aircraft and exponential in k
- Many interesting scheduling problems reduce to a shortest path computation on a variant of the basic k-CPS network, solved by dynamic programming
- Precedence constraints make the problem *easier* to solve (captured by simply removing certain nodes from the network)

Maximizing Throughput

- Objective: Given a sequence of aircraft, minimize the departure time of the last aircraft in the sequence (makespan)

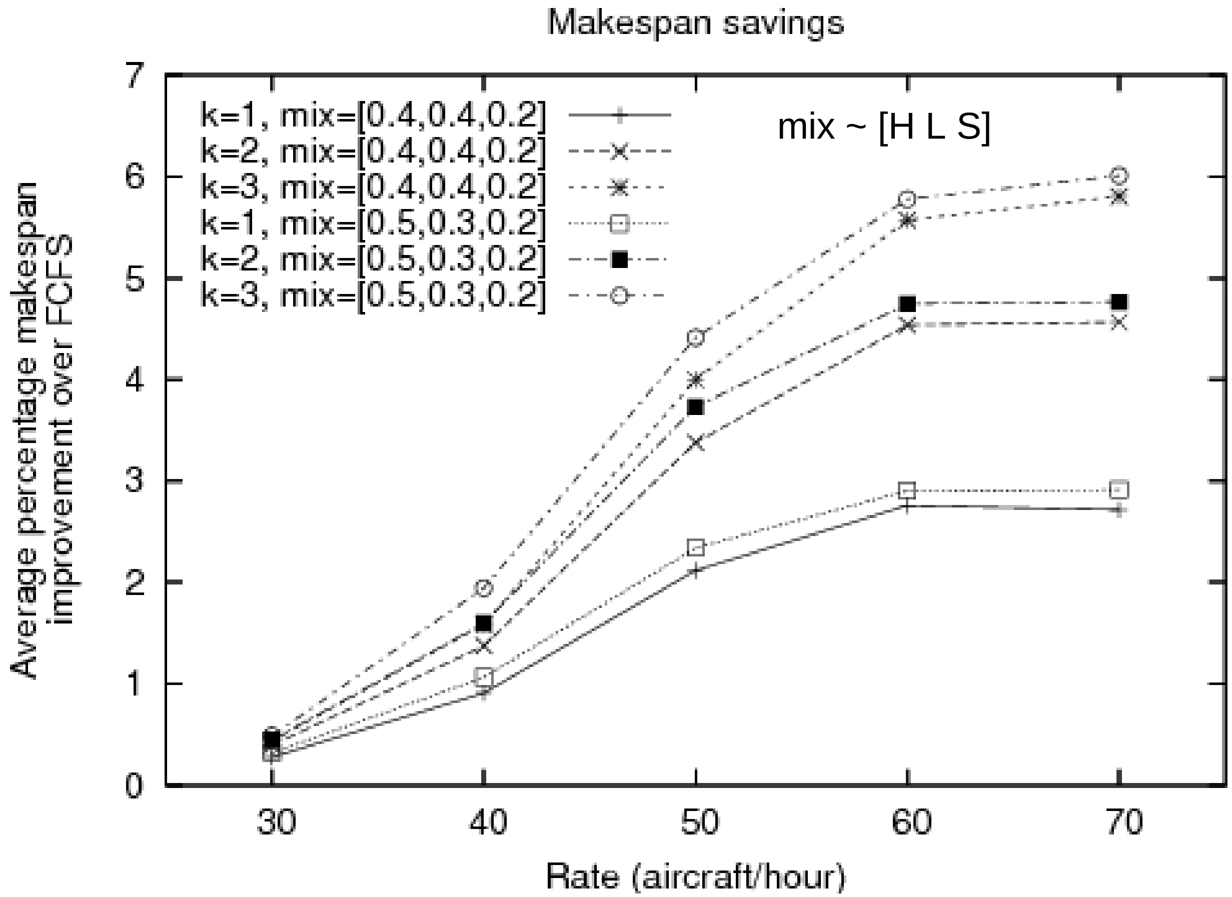
- Constraints:
  - CPS
  - Wake-vortex separation requirements
  - Precedence
  - Time windows of possible departure times (not necessarily contiguous)

- Computational complexity: Linear in number of aircraft

- Assumes the triangle inequality, *i.e.*, it is sufficient to ensure pairwise separation of successive aircraft in sequence
  - Aircraft i,j,k with minimum separations s_{ij}, s_{jk} and s_{ik}
  - Triangle inequality: $s_{ij} + s_{jk} \geq s_{ik}$

Monte Carlo Simulations

- Benefit depends on heterogeneity of aircraft types
- 3-CPS beneficial only for high rates
- Marginal benefit decreases as number of position shifts increases



Weighted sum of departure times

- Special cases: Average delay, weighted sum of average delay and throughput, weighted sum of delay costs

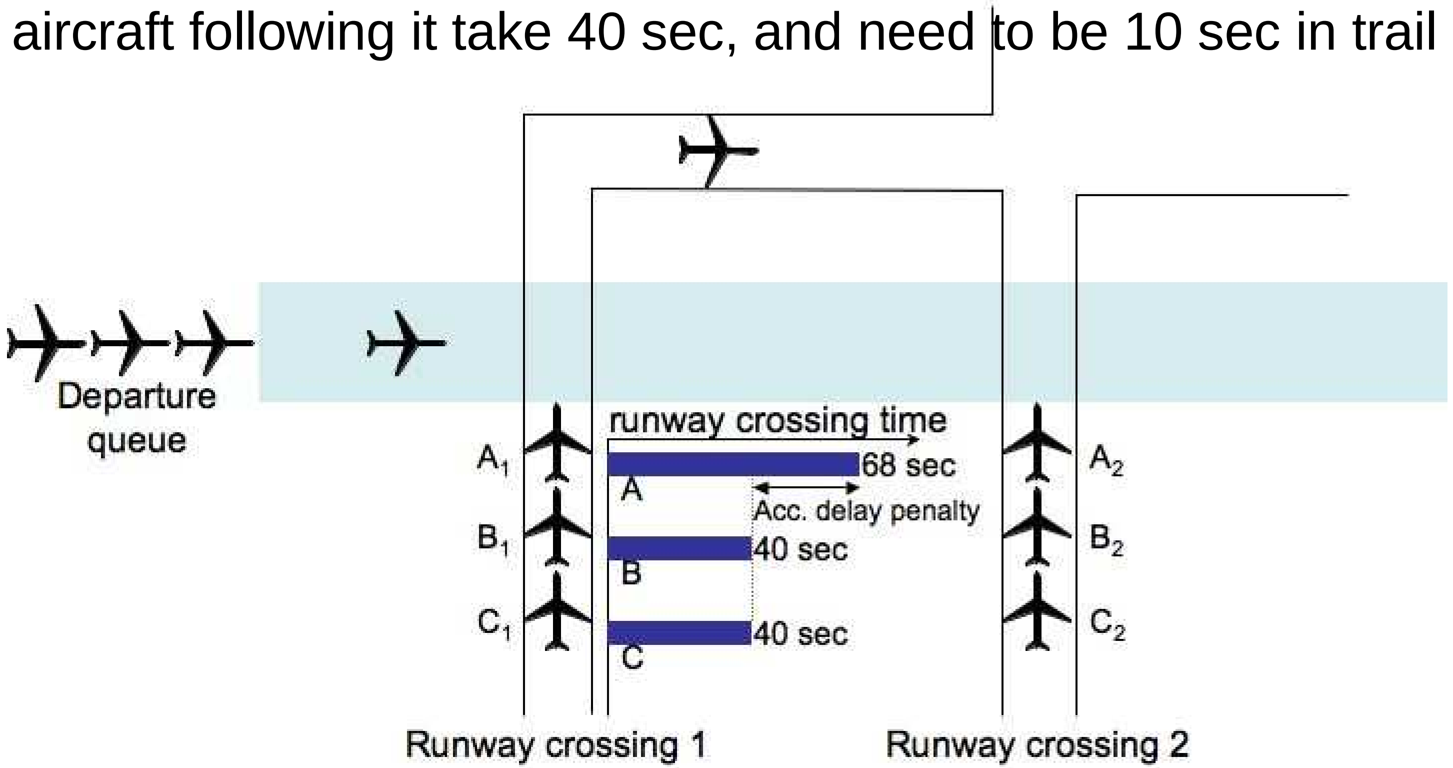
- Objective: Minimize a weighted sum of departure times

- Constraints:
  - CPS
  - Wake-vortex separation requirements
  - Precedence
  - Arrival time windows

- Computational complexity:
  - Approach 1: Quadratic in number of aircraft
  - Approach 2: Linear in number of aircraft and quadratic in length of planning period

Active runway crossings

- Arriving (or departing) aircraft may need to cross an active runway to reach their gates (or departure queue)
- First aircraft to cross after a departure takes 68 sec (acceleration delay penalty), aircraft following it take 40 sec, and need to be 10 sec in trail



Active runway crossings

- Assume each crossing stream maintains FCFS
- Objective: Minimize time to complete operations, or weighted sum of landing times in the presence of runway crossings
- Constraints:
  - CPS for departure stream
  - Wake-vortex separation requirements
  - Precedence in departure and crossing streams
  - Maximum wait time restriction on crossing streams
- Complexity: (Complexity of problem without crossings)$\times c.n_1^{(2c+1)}$ (number of aircraft in the largest runway crossing stream, n_1 and number of crossing streams, c are both typically small)

Runway crossing example

- Departure stream n=6, k=1 with optimal schedule (no crossings)

Aircraft	2	1	3	4	5	6
Time (sec)	0	60	150	270	330	390

- Two runway crossing aircraft A and B arrive and must cross in the intervals [160,340] and [200,480], insufficient spacing in current schedule to accommodate crossings

ROT of departures: 55 sec

First aircraft to cross after a departure takes 68 sec (acceleration delay penalty), aircraft following it take 40 sec, and need to be 10 sec in trail

- Naïve solution

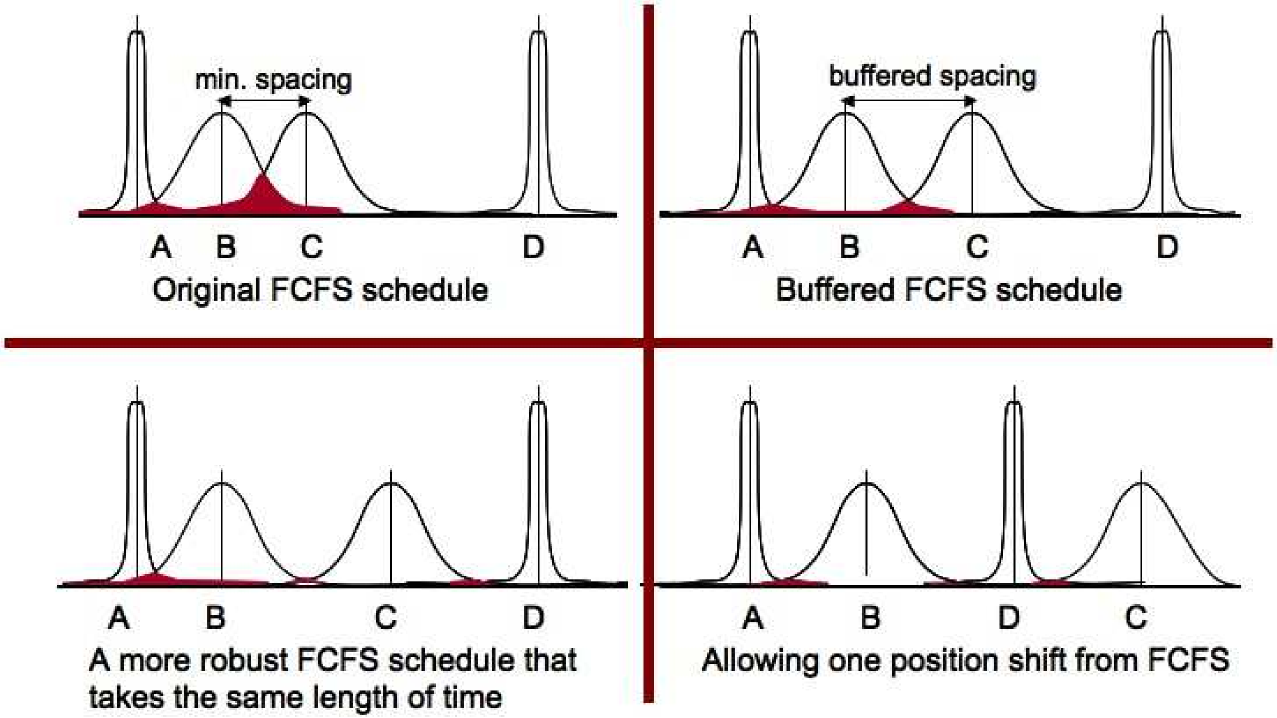
Aircraft	2	1	3	**A**	4	5	6	**B**
Time	0	60	150	**205**	273	333	393	**448**

- Optimal solution

Aircraft	2	1	3	**A**	**B**	4	5	6
Time	0	60	150	**205**	**243**	283	343	403

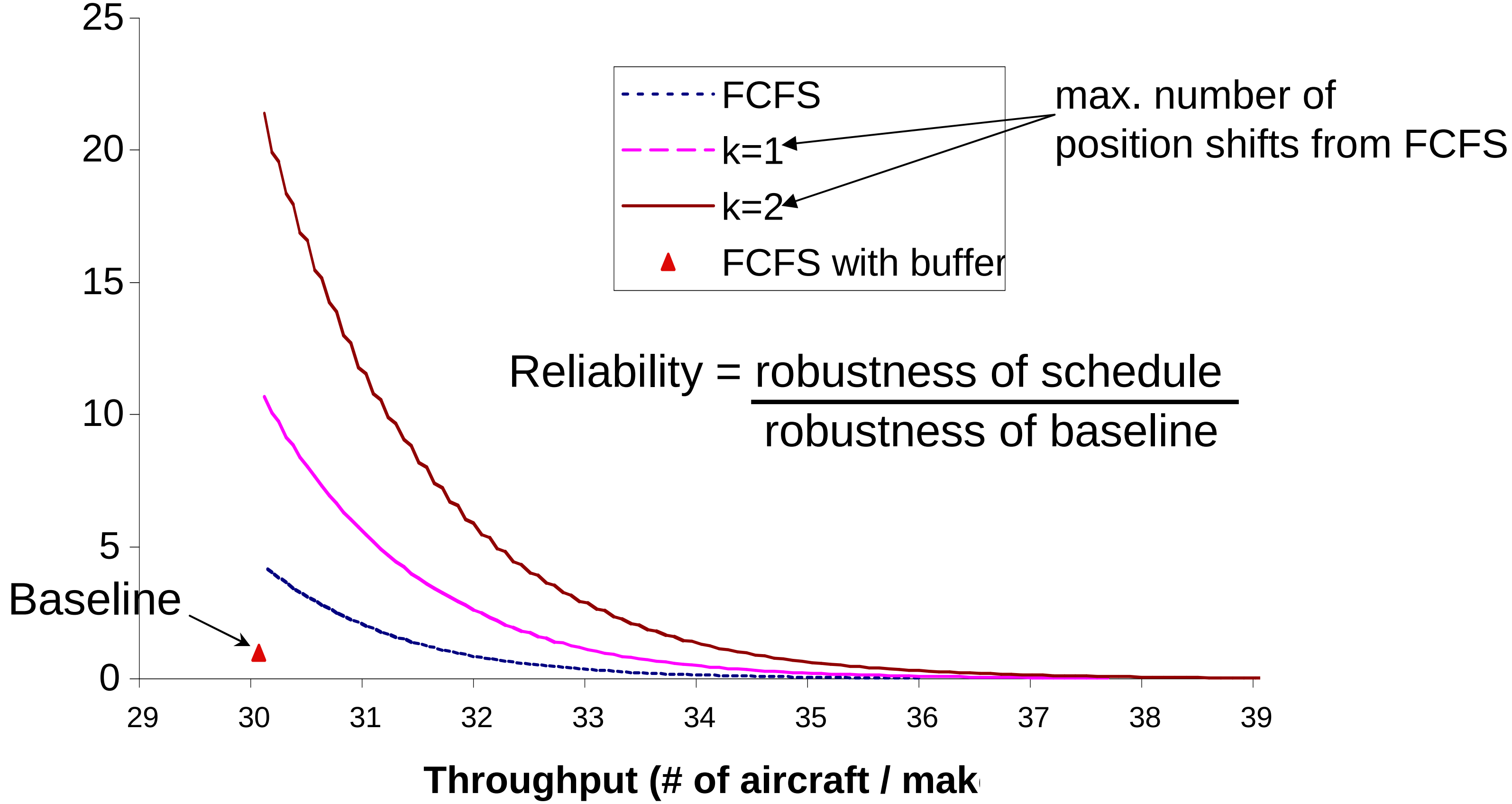
Robust runway scheduling

- Aircraft cannot exactly confirm to runway schedules due to uncertainty in taxi times and pushback times
- Different aircraft could have different levels of uncertainty due to precision taxiing, equipage, etc.



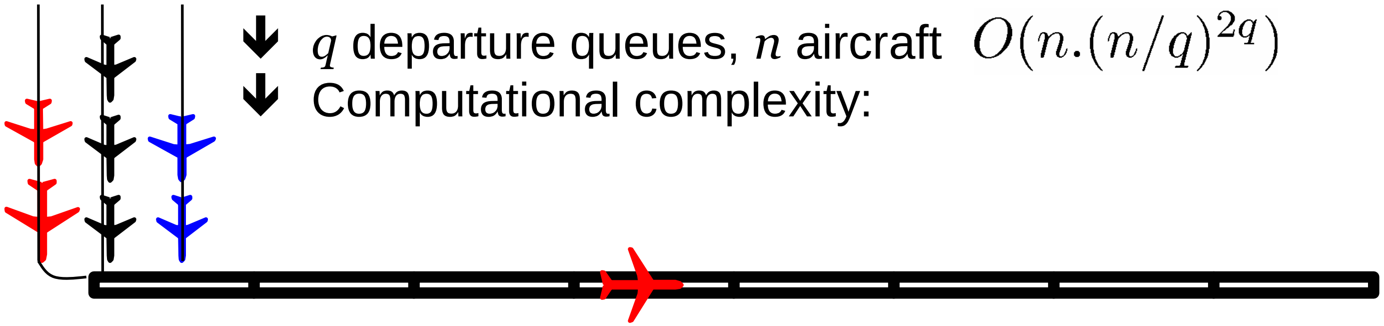
Robust runway scheduling

- Objective is to compute the trade-off between the throughput and robustness (likelihood that the separation requirements are violated)



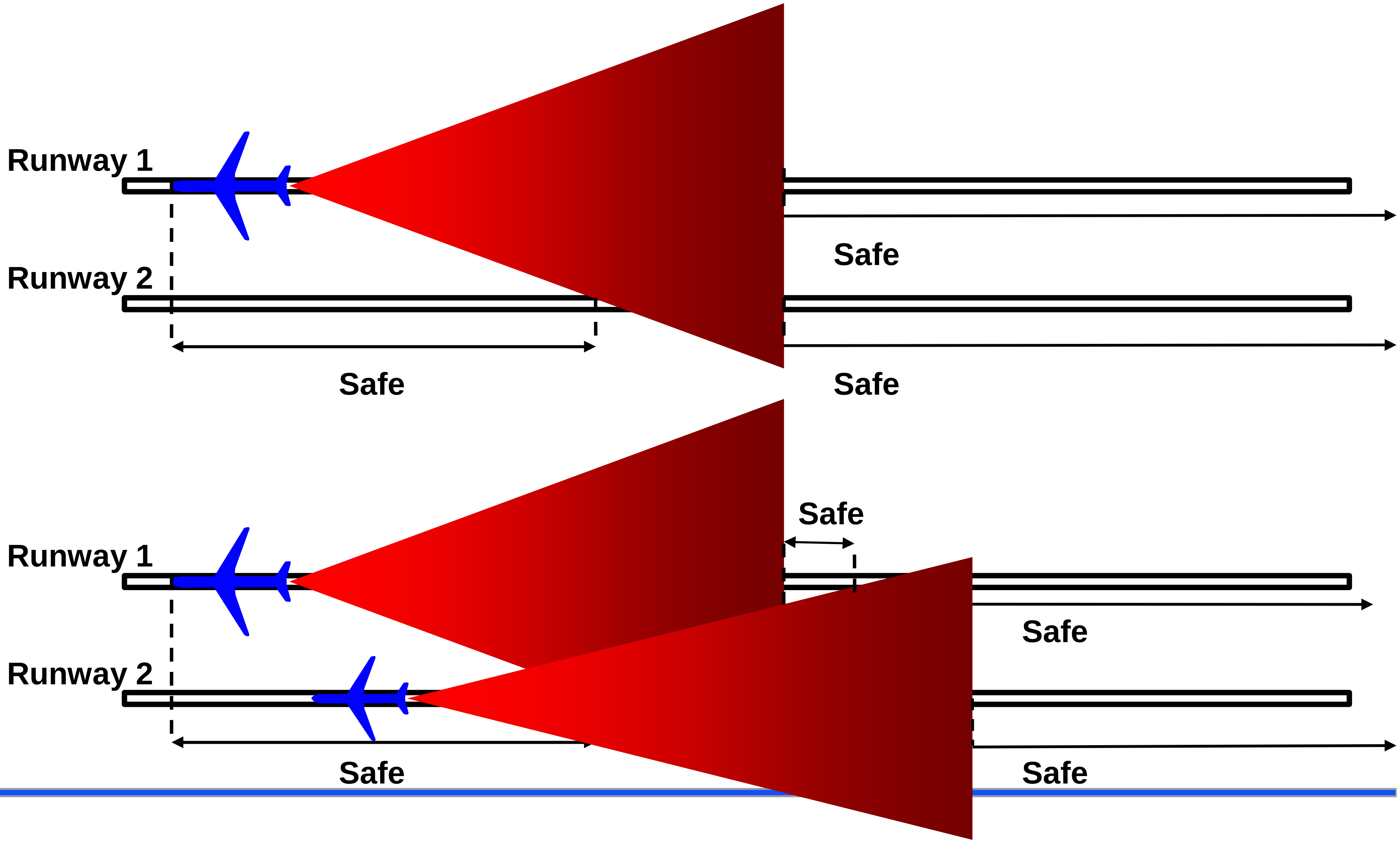
Extensions

- If triangle inequality is violated, problem becomes harder to solve
  - Modified network is larger, and its size depends on planning horizon
  - Can handle all previous constraints
  - E.g., downstream Miles-in-Trail constraints, multiple dependent runways
- Multiple runways
  - Can handle departures with pre-assigned runways, runway balancing, and scheduling in Closely Spaced Parallel Runways (CSPRs)
  - Computationally more intensive (still linear in number of aircraft but polynomial in the length of planning horizon)
- Multiple departure runway queues (departure staging areas)



- q departure queues, n aircraft $O(n.(n/q)^{2q})$
- Computational complexity:

Arrival side: Closely Spaced Parallel Approaches



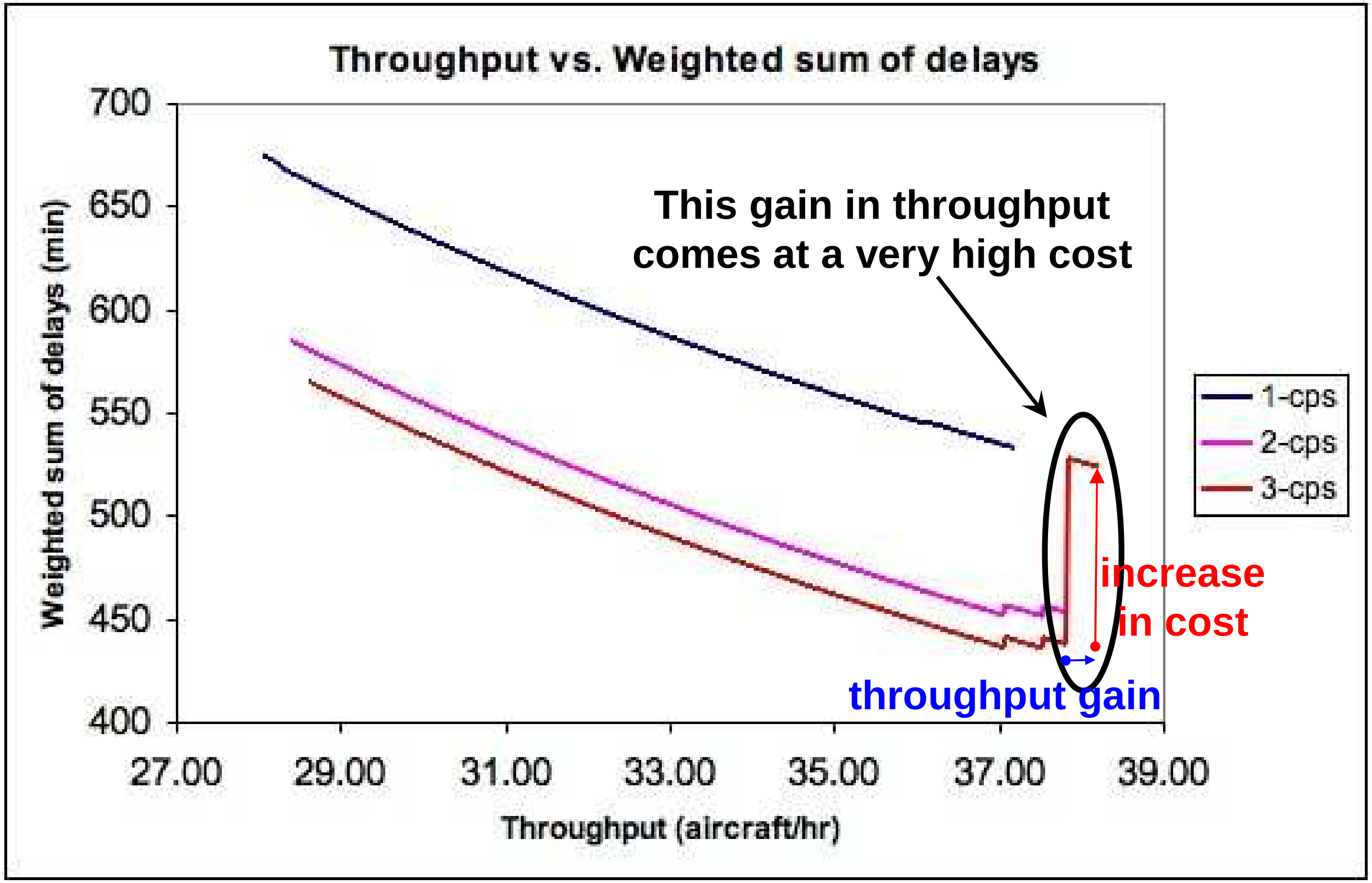
Advantages of this common framework

- Having a computationally efficient framework (CPS network) for solving departure scheduling problems enables real-time implementations

- CPS framework can handle a variety of objective functions enables tradeoff studies, such as
  - ☐ Tradeoffs between robustness and throughput
  - ☐ Tradeoffs between average delay and throughput
  - ☐ Tradeoffs between weighted sum of delays and throughput

Tradeoffs between throughput and weighted sum of delays

Randomly generated sequence, 40% Heavy, 40% Large, 20% Small
Delay costs of Heavy and Large are 9 x (Delay cost of Small aircraft)



[Lee and Balakrishnan, 2007]

Summary

- Developed the Constrained Position Shifting (CPS) framework for departure scheduling that can optimize a wide range of objective functions
  - Enables efficient and equitable departure scheduling
  - Computationally efficient solution is amenable to real-time departure planning
- Single framework for different variants of departure scheduling problem also enables tradeoff studies between different metrics
  - Robustness vs. throughput
  - Fuel burn (emissions) vs. throughput
- Framework also extends to arrival scheduling, including Closely Spaced Parallel Approaches