Efficient Trajectory Options Allocation for the Collaborative Trajectory Options Program

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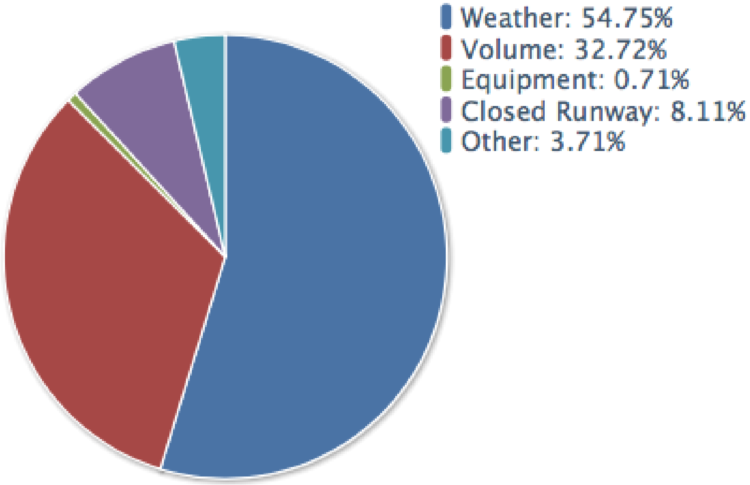
Traffic Flow Management (TFM)

- Main function: balancing demand and capacity
- Severe (convective) weather:
  - Reduces the airspace capacity
  - Major cause of disruptions and delays in the National Airspace System (NAS)



Bureau of Transportation Statistics: Causes of National Aviation System Delays. May, 2012 – May, 2017

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- Severe (convective) weather:
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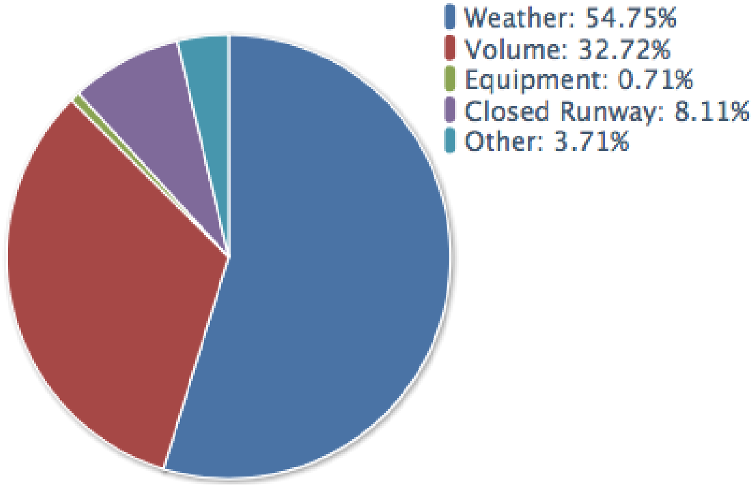
- Traffic Management Initiatives (TMIs):
  - Ground Delay Program (GDP)
  - Airspace Flow Program (AFP)
  - Collaborative Trajectory Options Program (CTOP)



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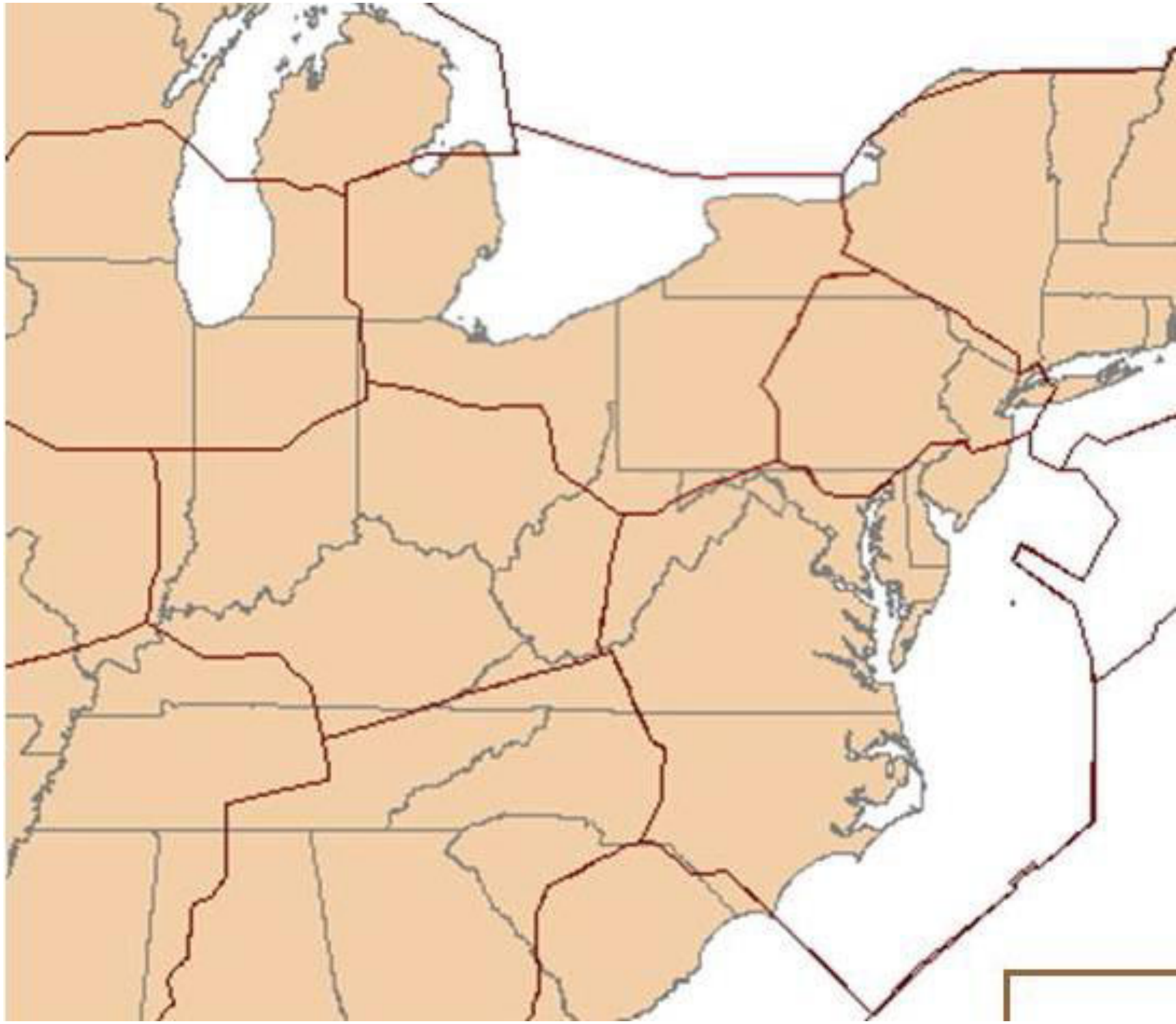

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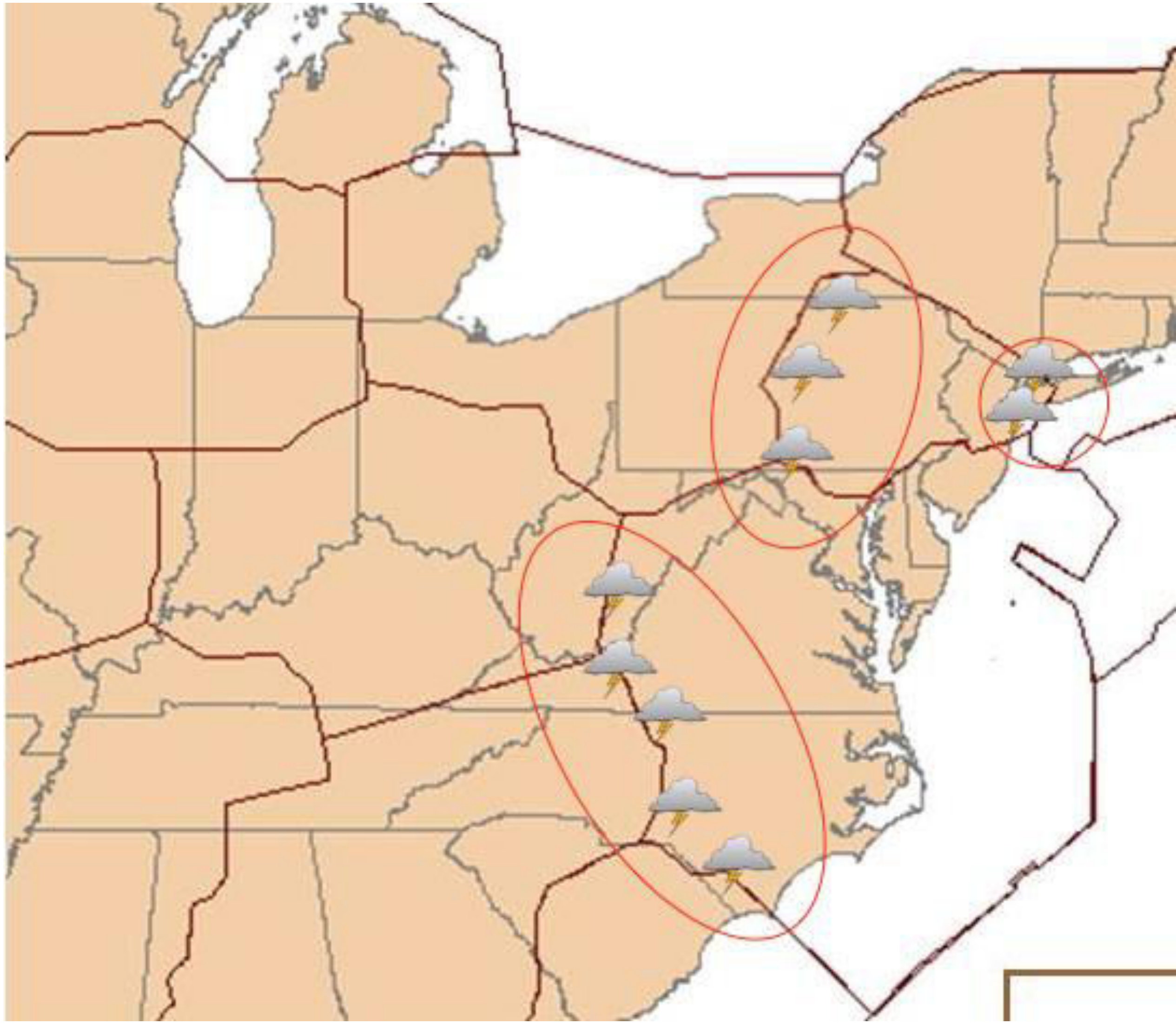
    - Weather forecast
    - Demand



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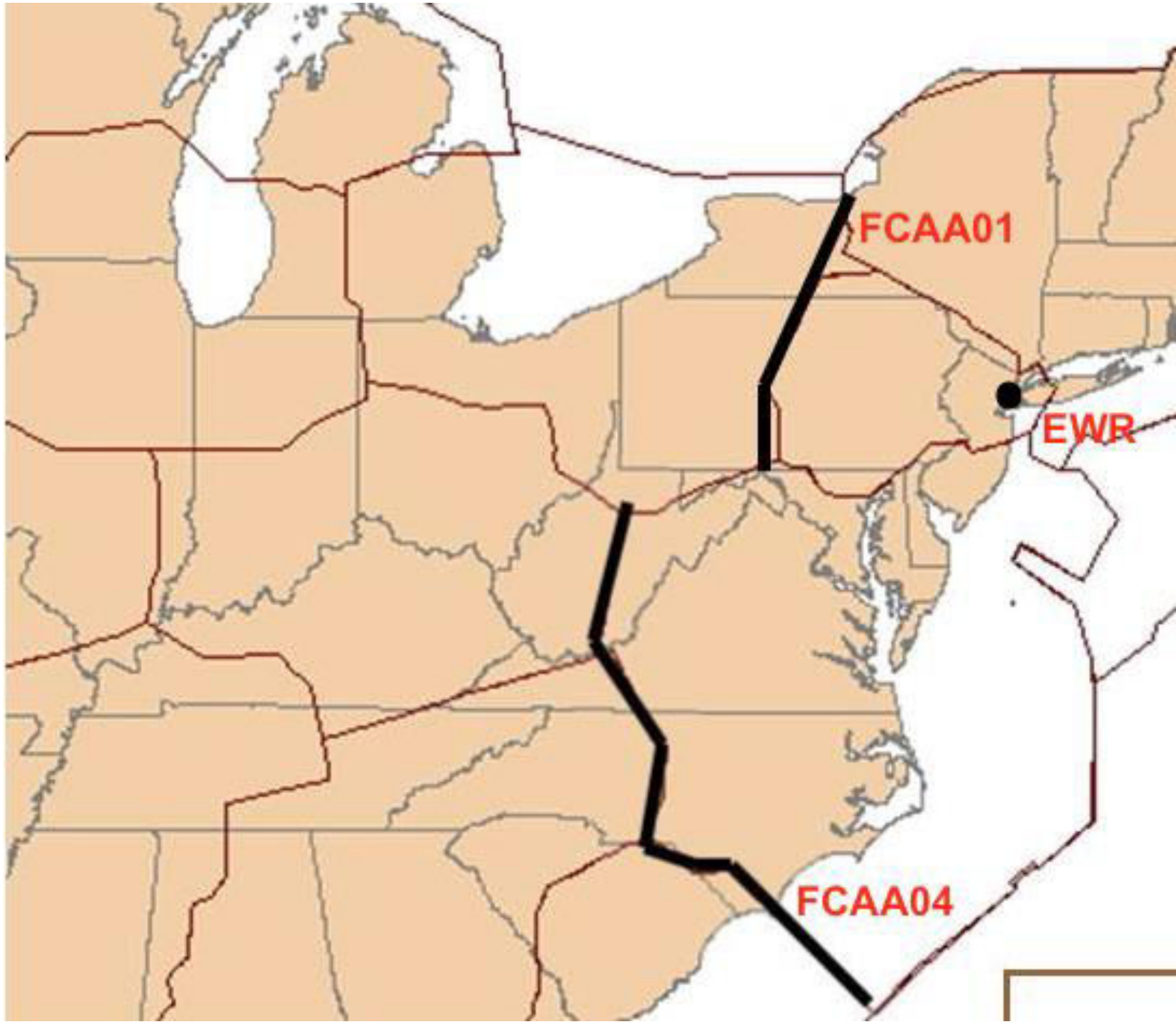

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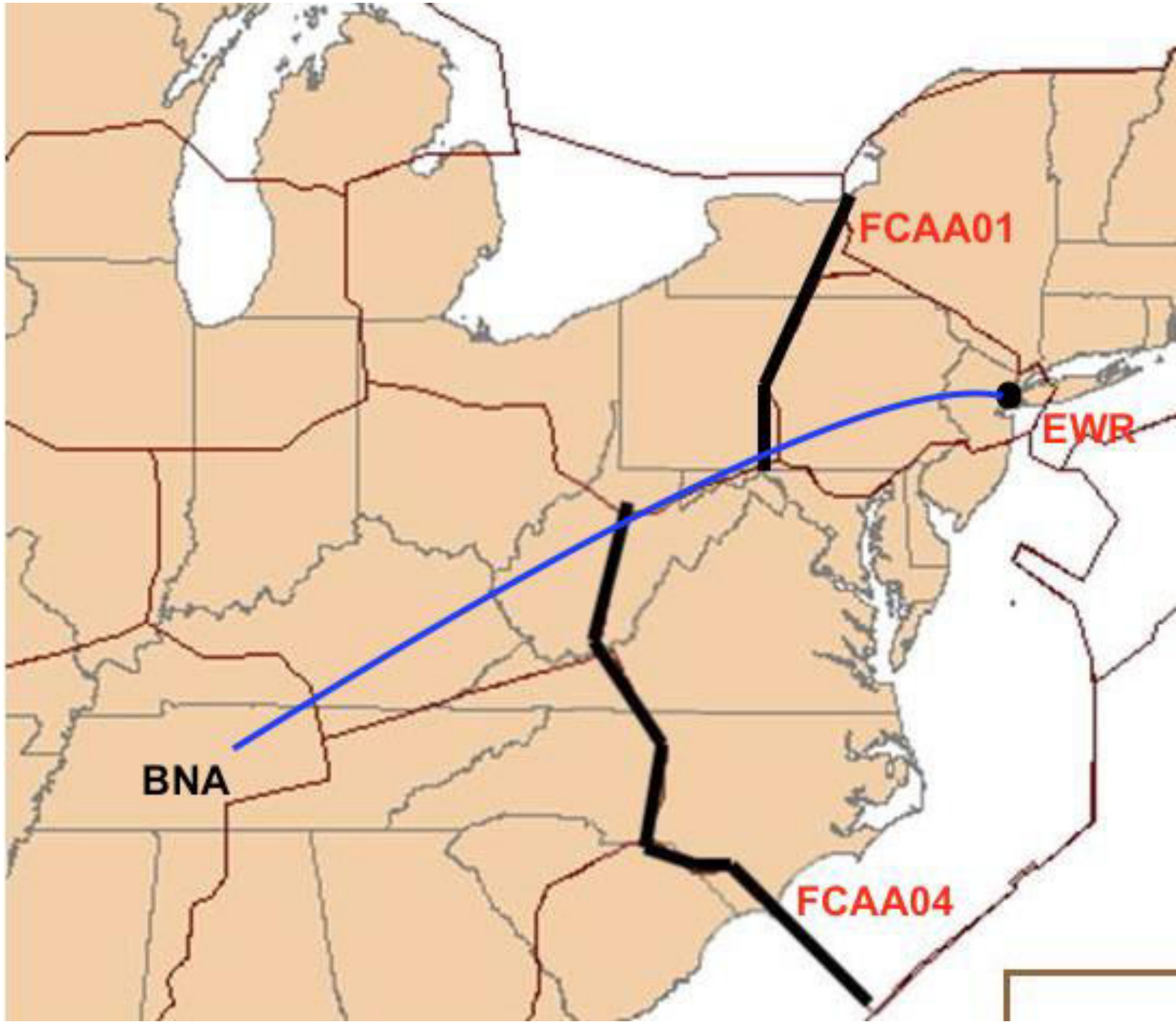

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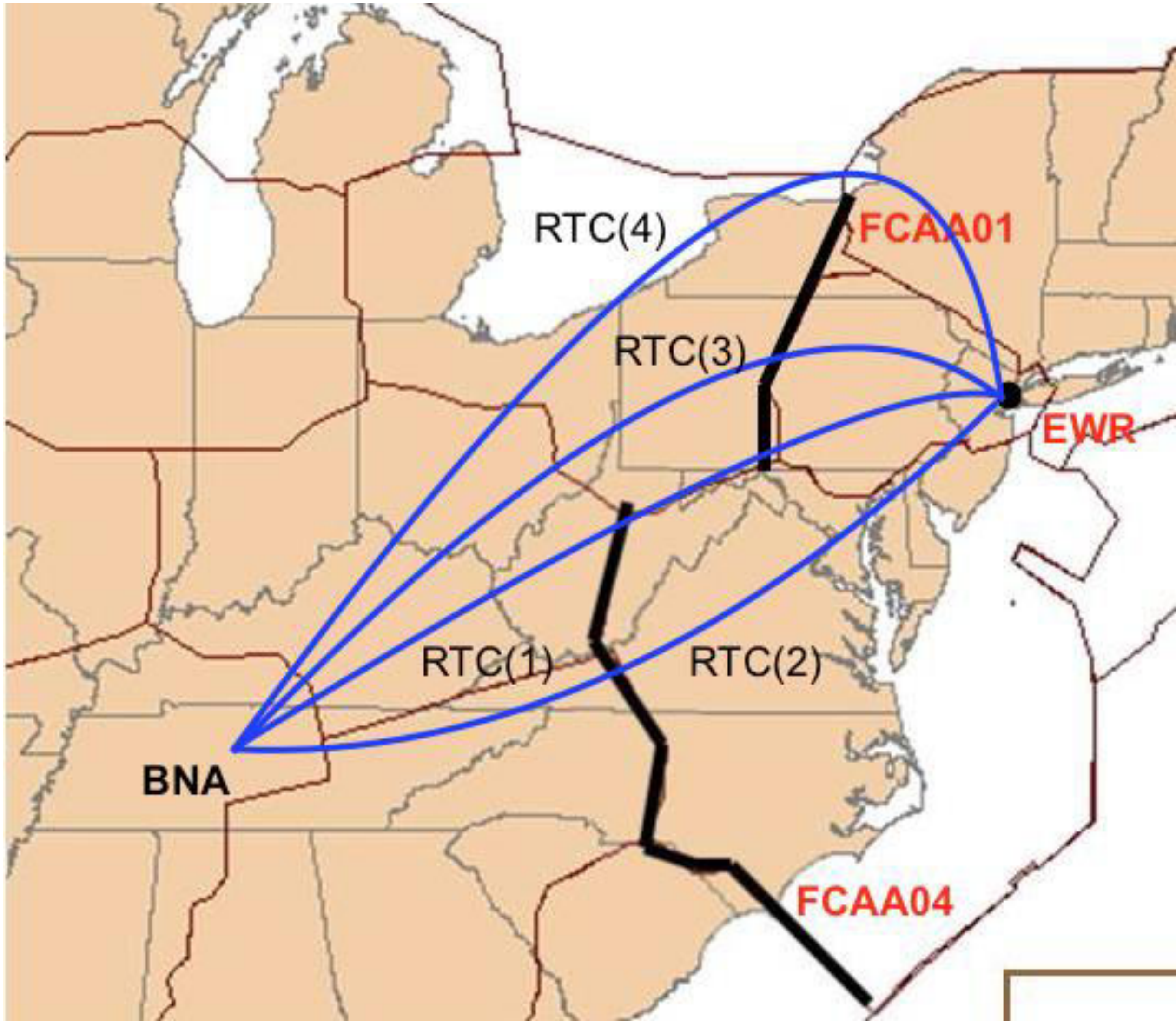

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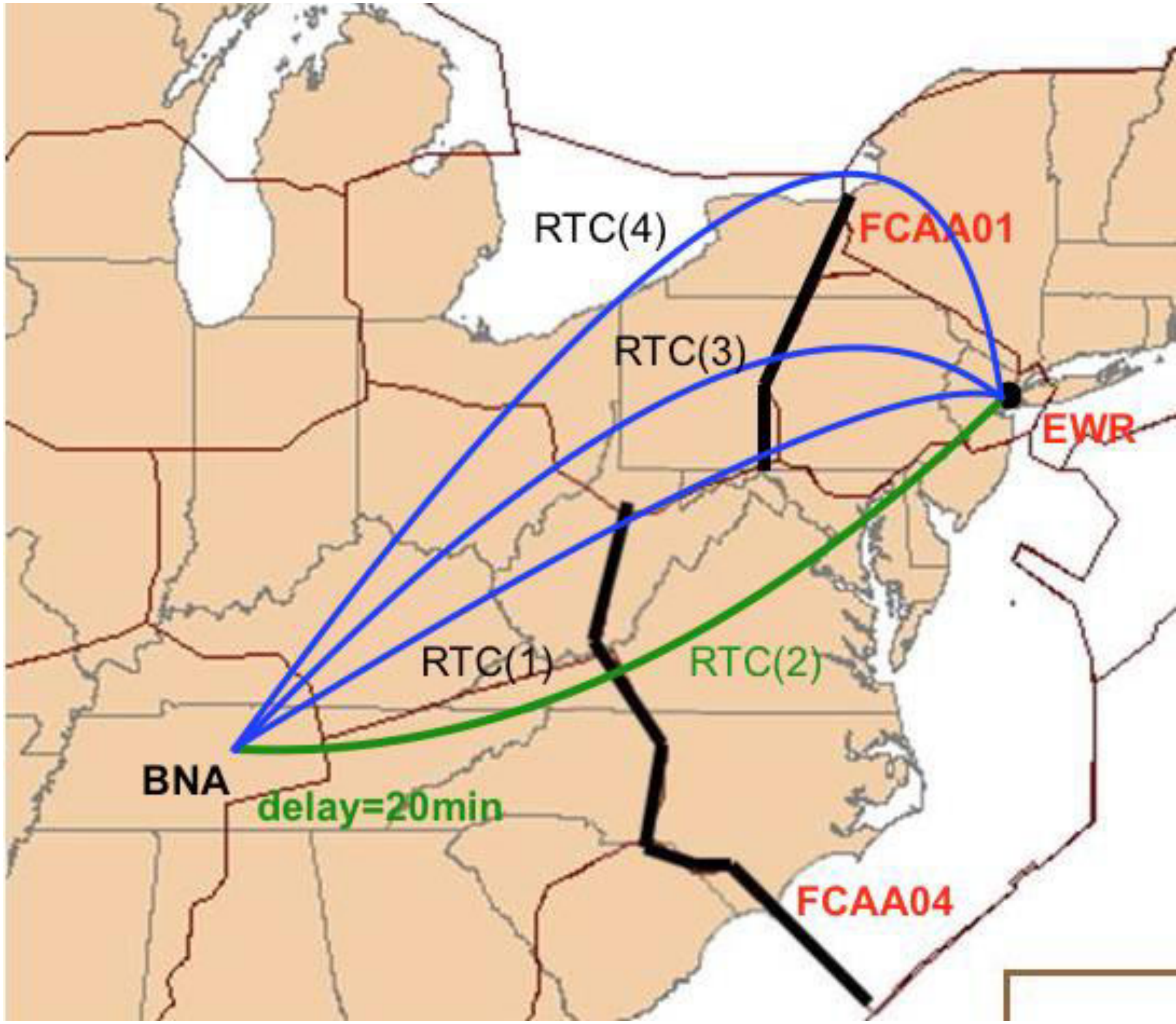

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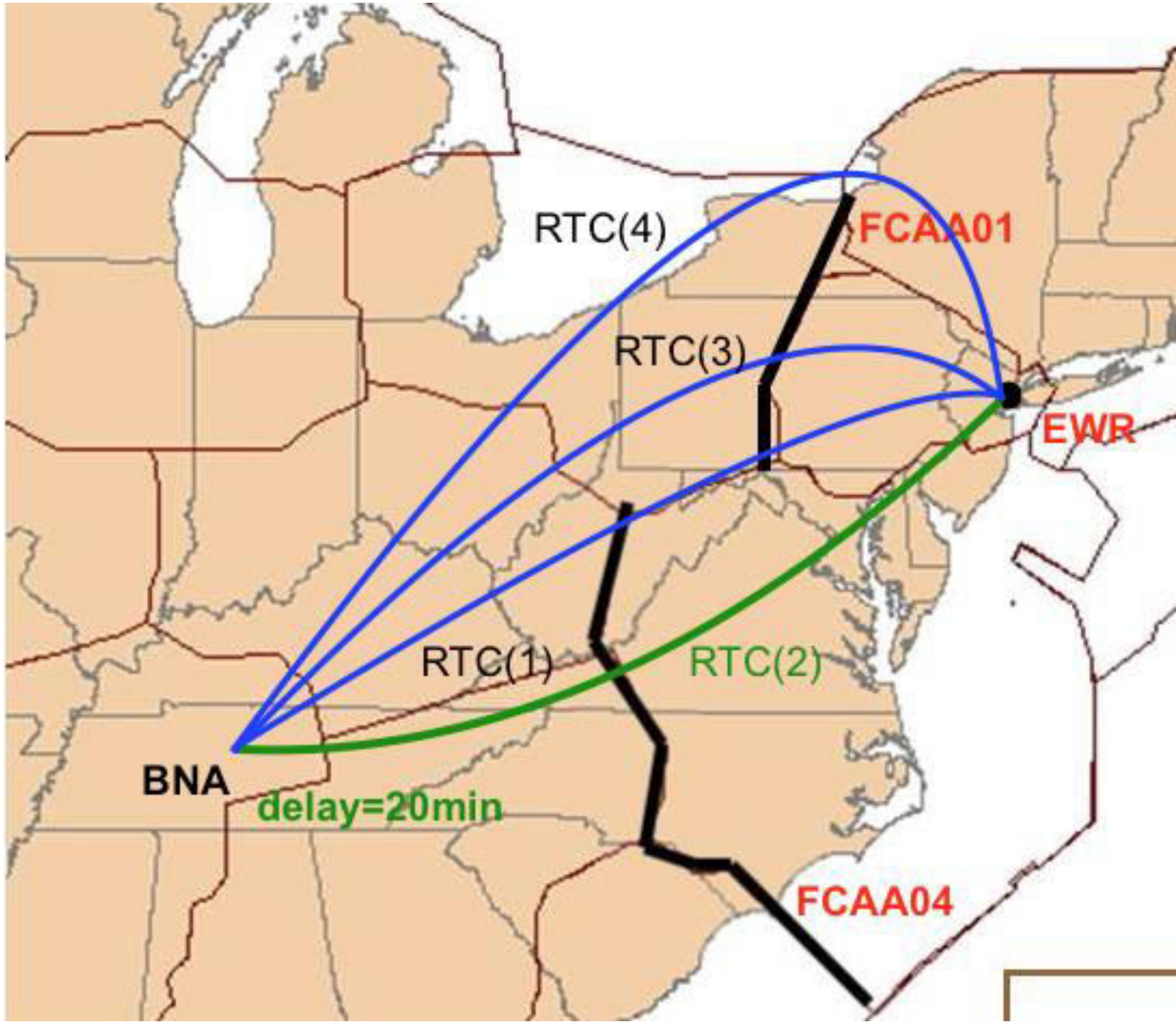

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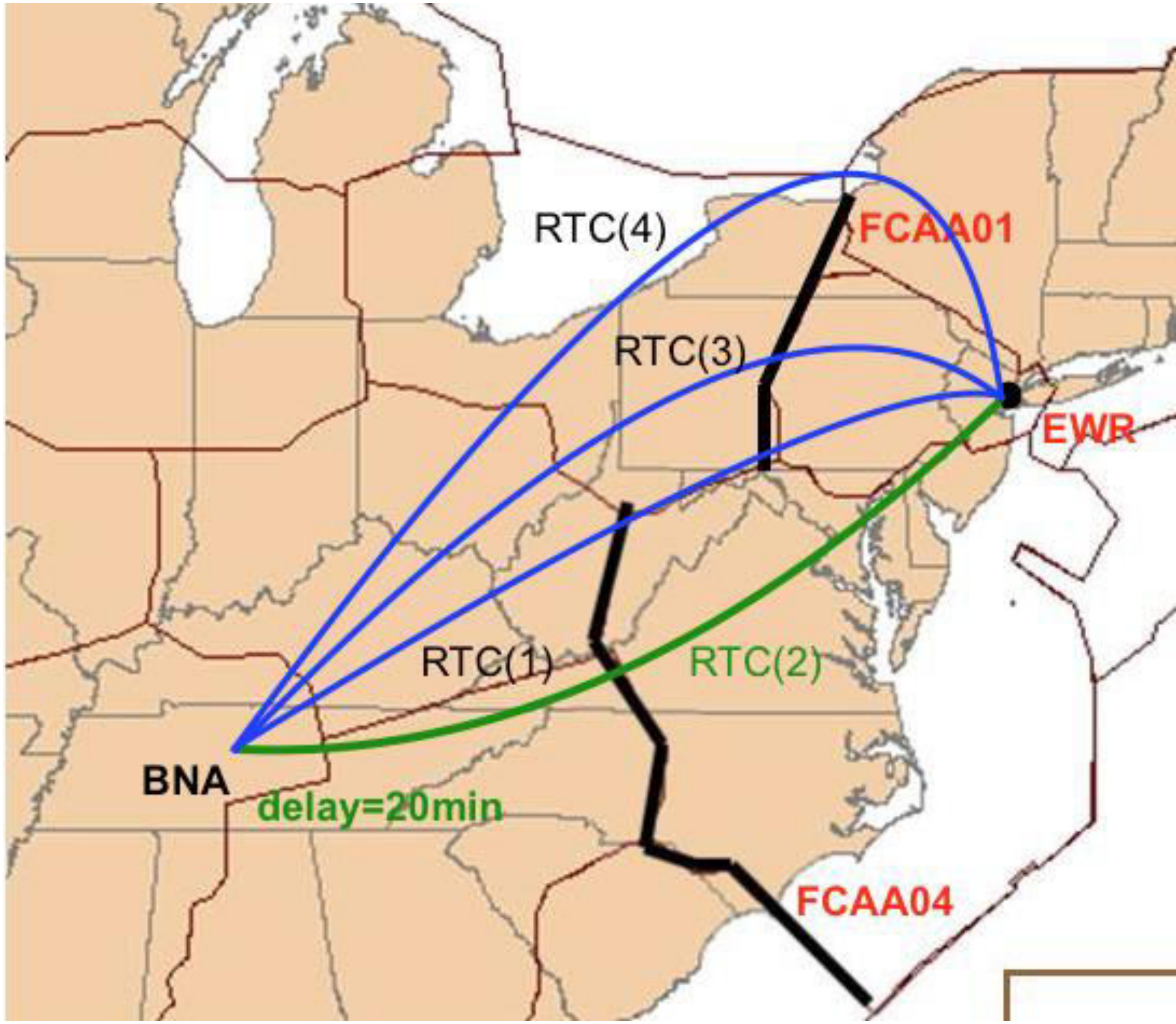
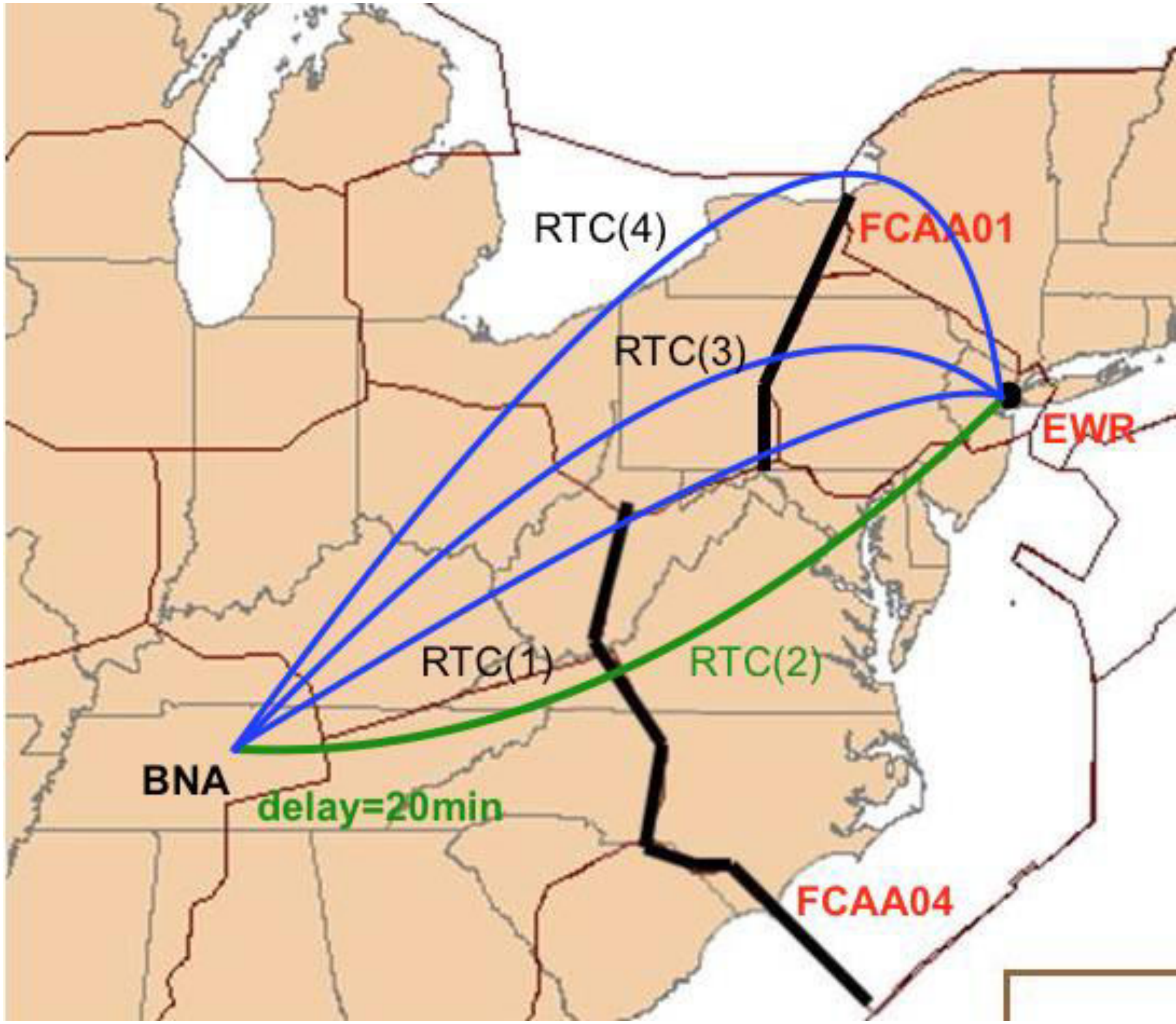


Problem statement

- Given
  - Flow Constrained Areas (FCAs)
  - Airline Trajectory Option Sets (TOSs)
- For each flight, assign
  - Route from Trajectory Option Set (TOS)
  - Ground delay
- Subject to
  - Flow Constrained Area (FCA) capacity constraints



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- Current approach
  - Based on First Come First Served principle
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  - Consecutive FCAs not supported
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- Proposed approach
  - Global optimization
  - Constraints at multiple FCAs satisfied simultaneously
  - Airborne delay accounted for
  - Equity metric in optimization

Resource allocation problem: overview

Resources	Performance metrics	Allocation algorithms

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- For each flight, calculate its Initial Arrival Time (IAT)
  - For each route option from TOS, calculate the Estimated Arrival Time (ETA) at its first (primary) FCA
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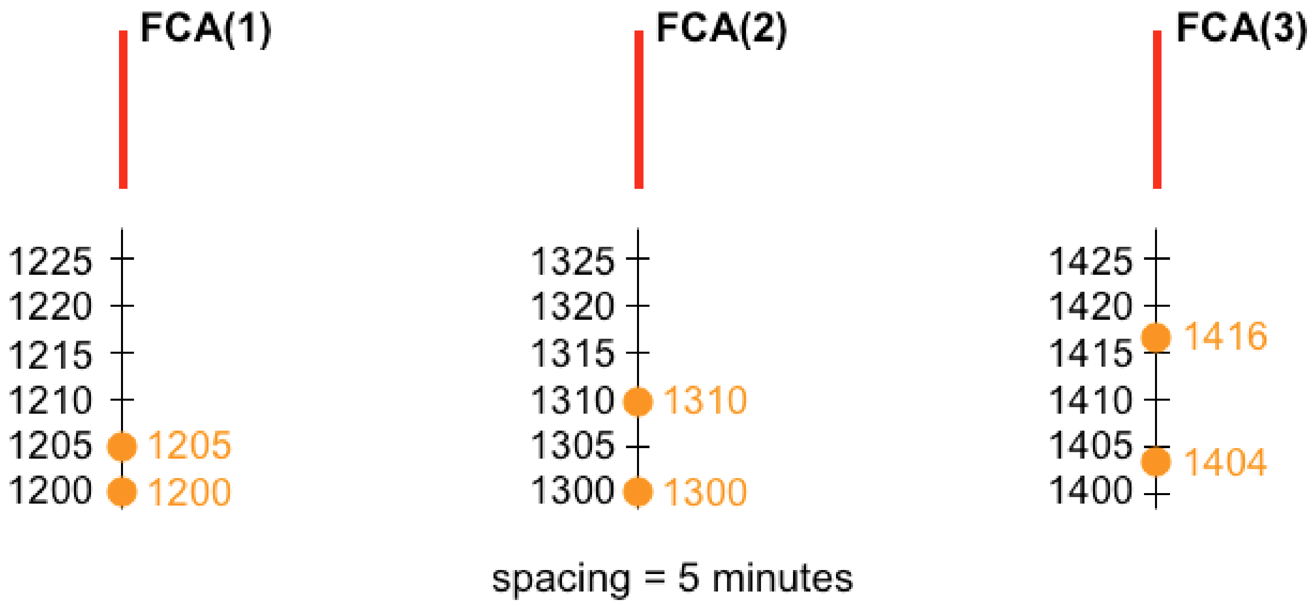
  - Choose the option with the least total cost
  - Assign the selected route and the associated delay to flight

RBS scheduling example



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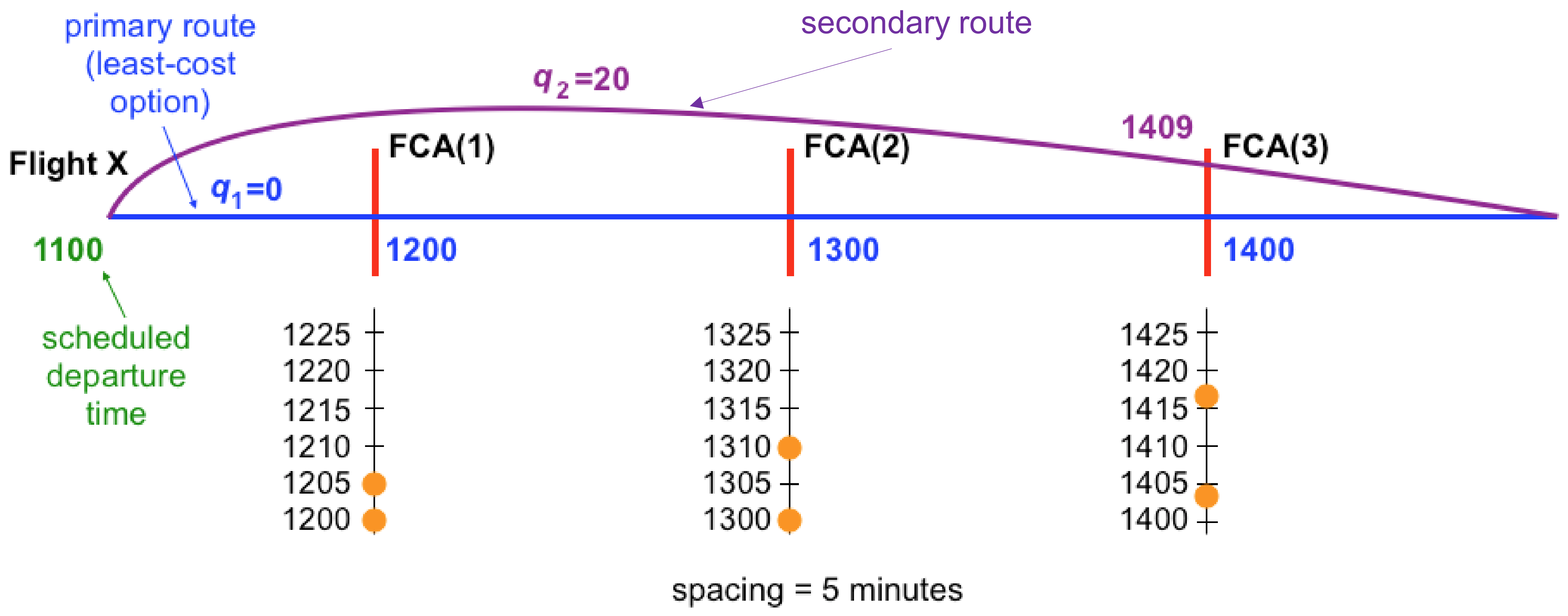

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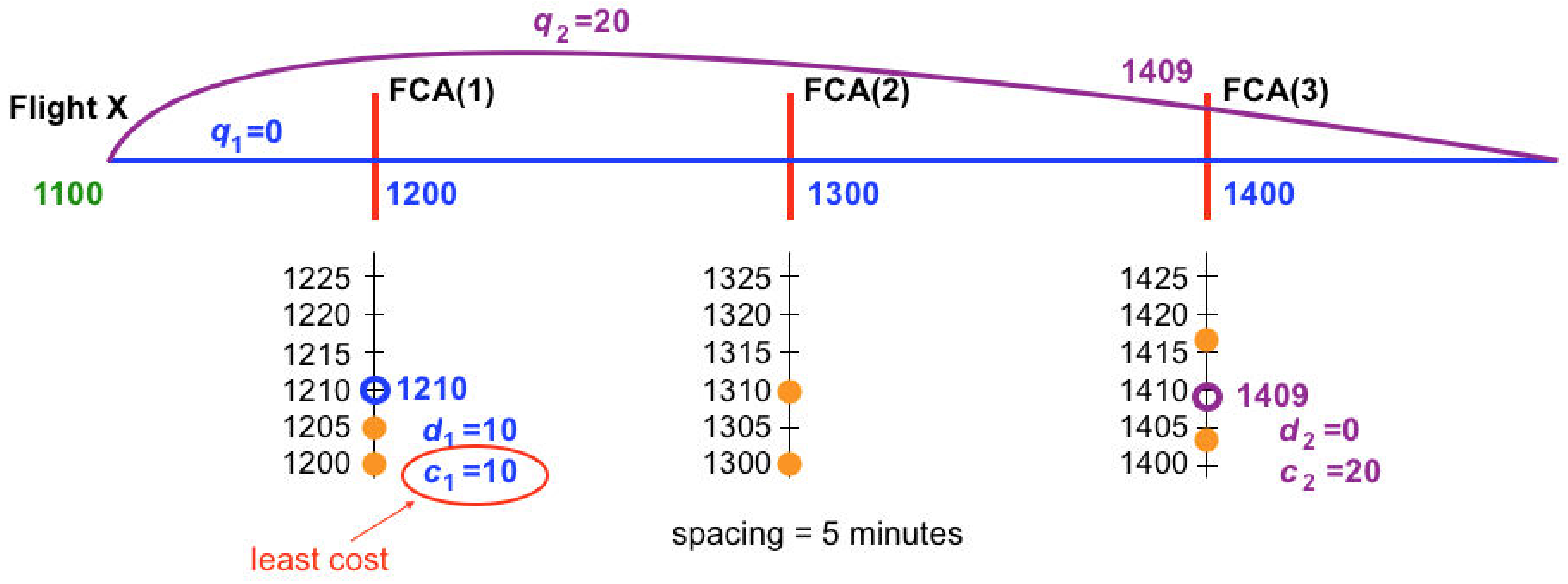

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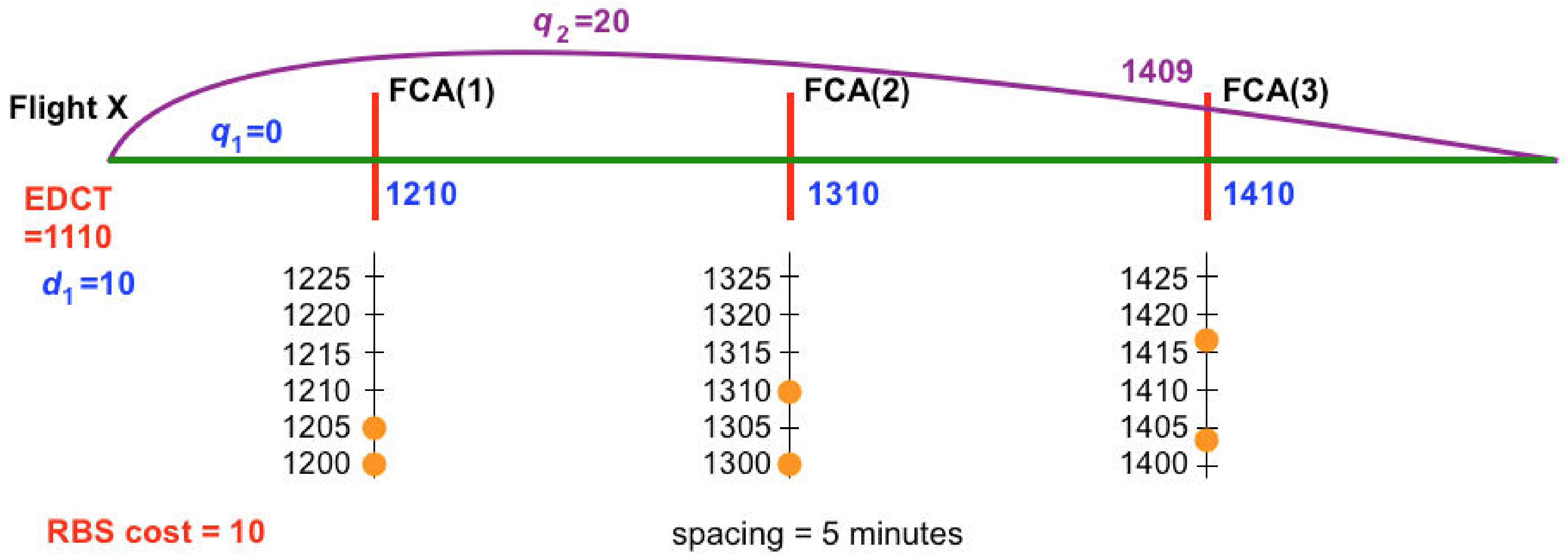

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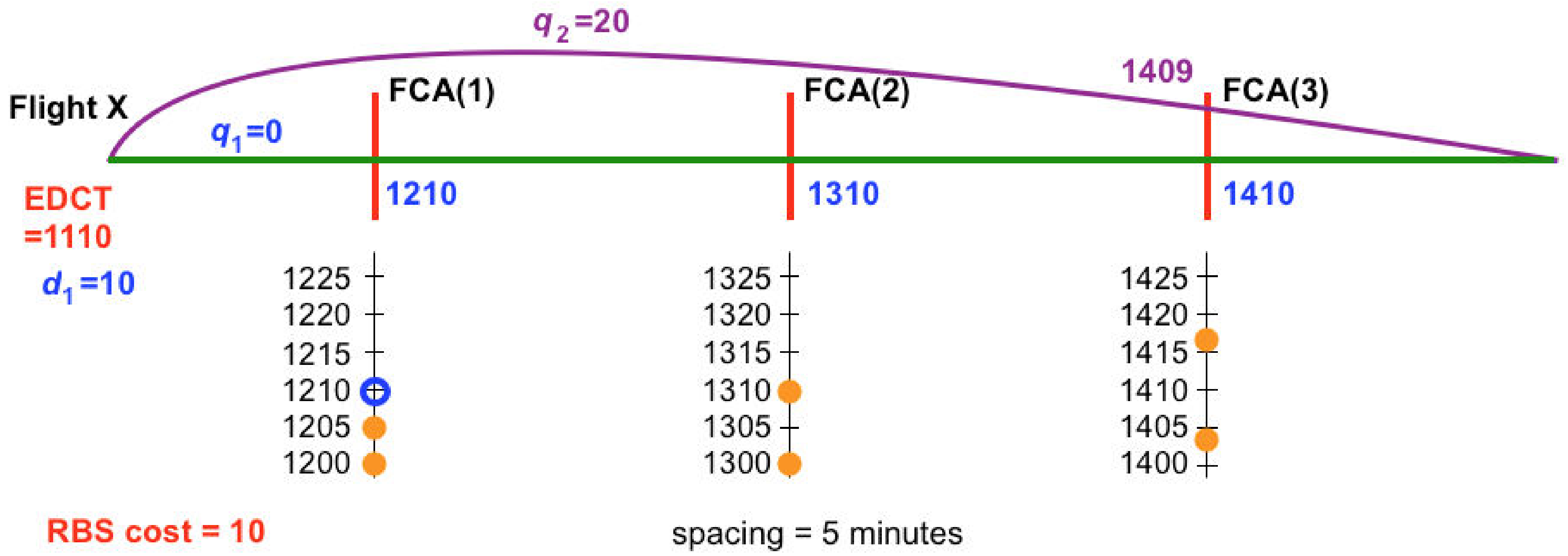

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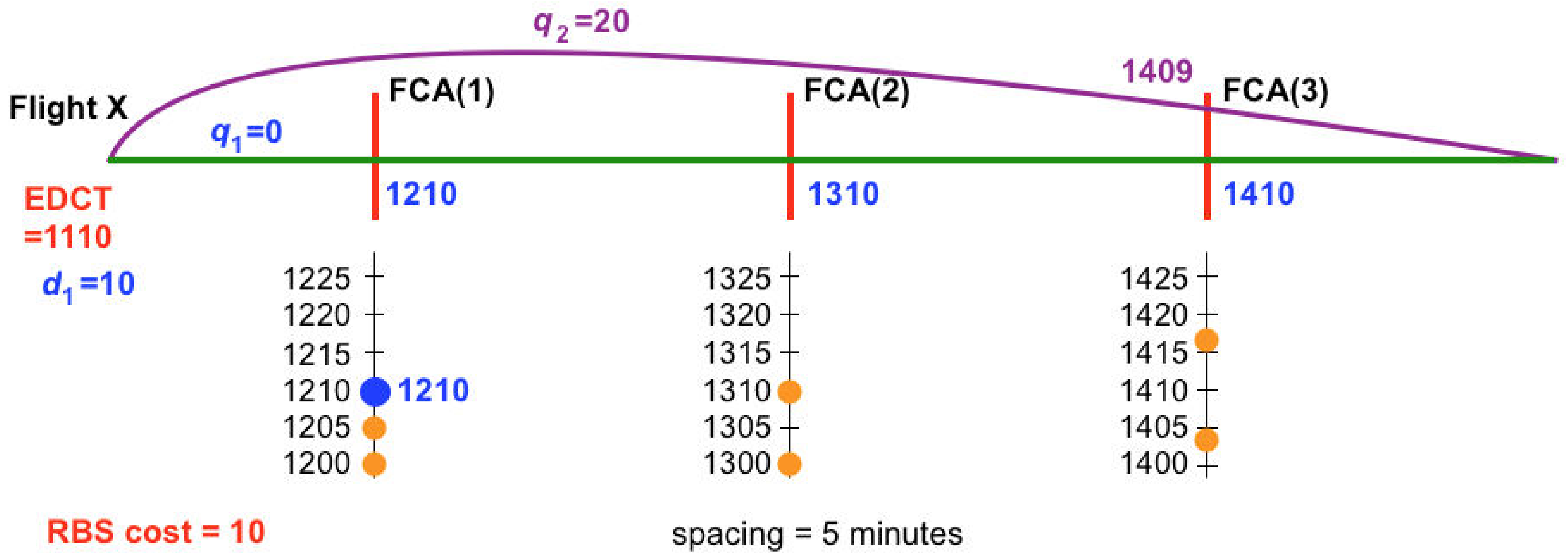

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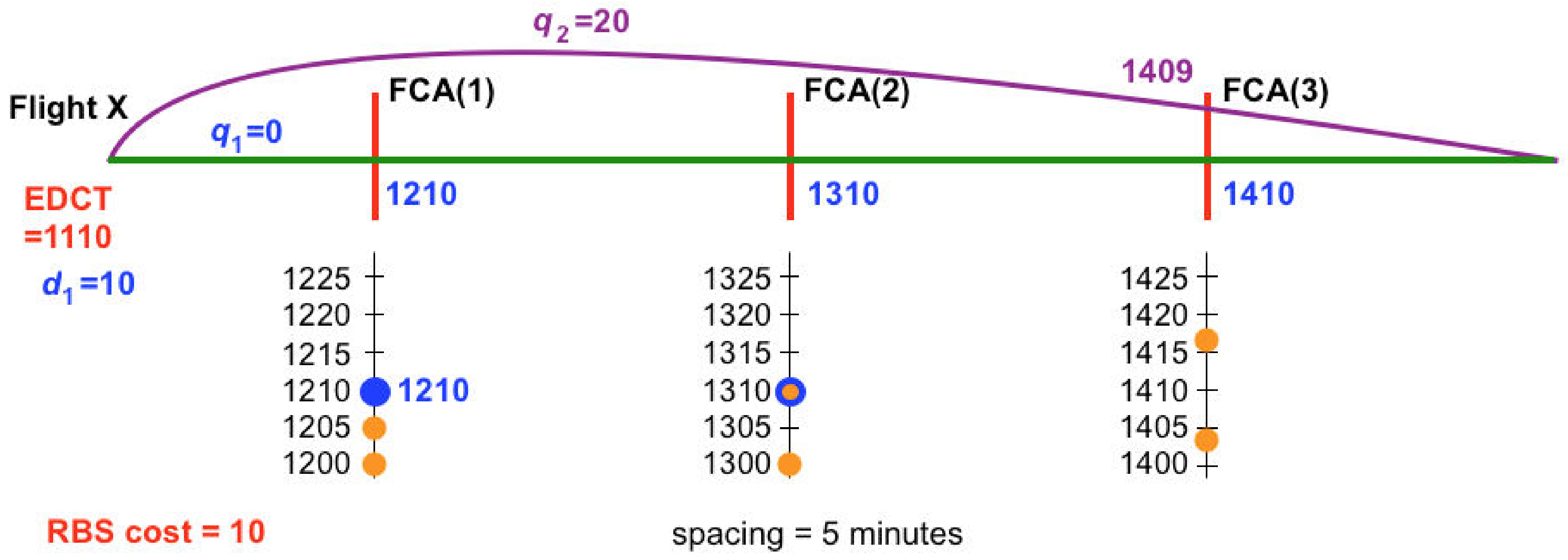

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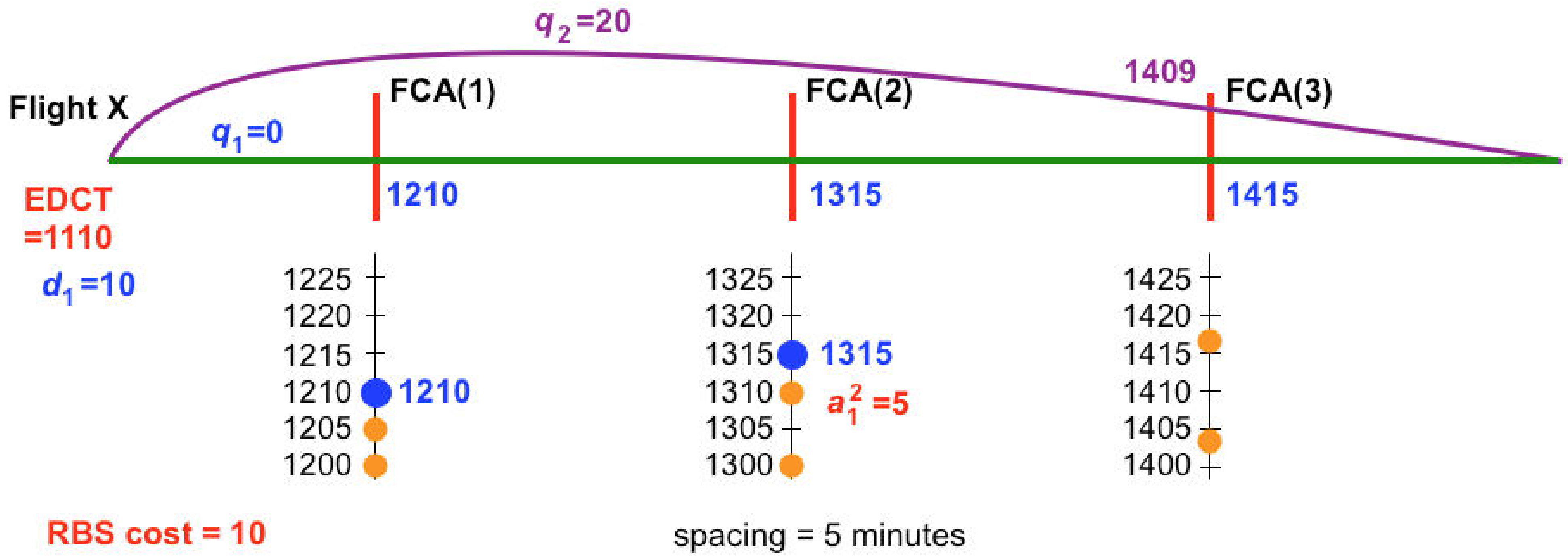

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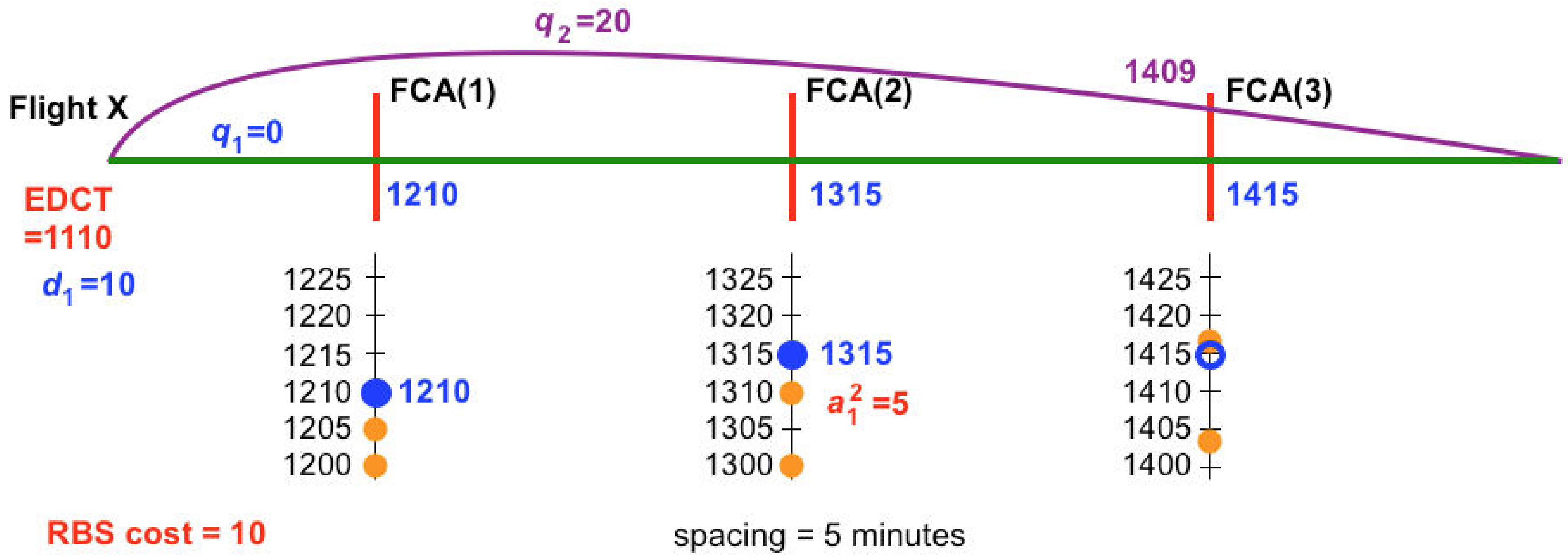

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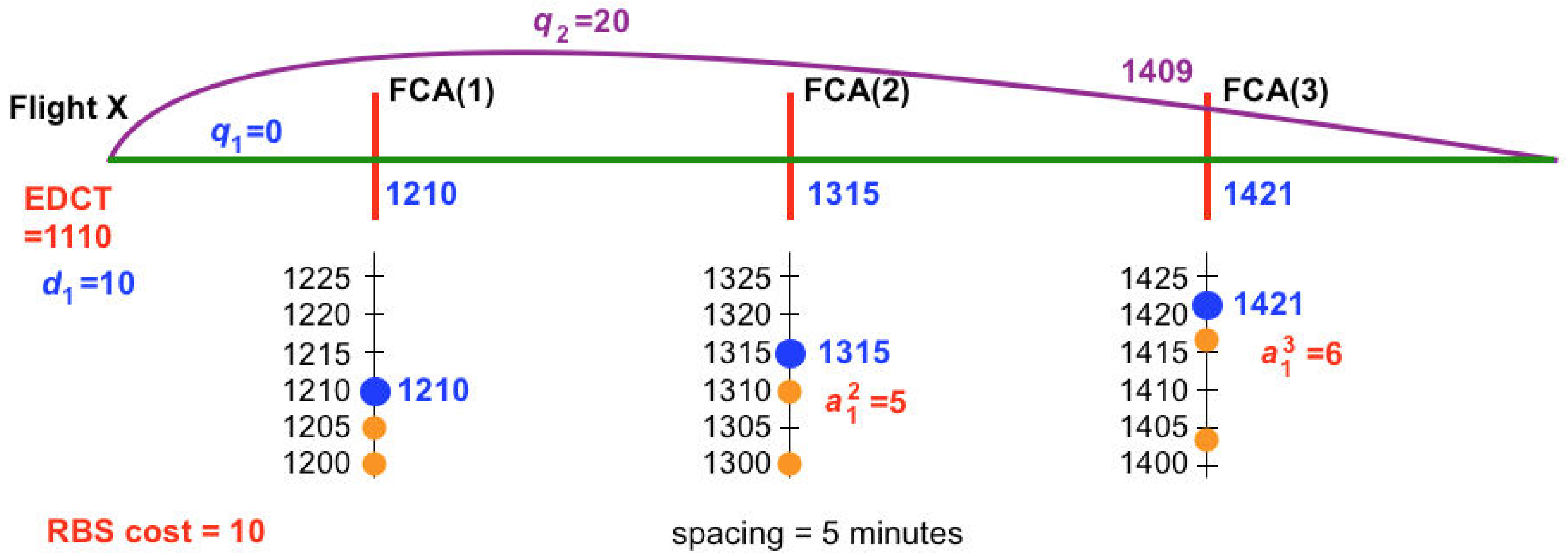

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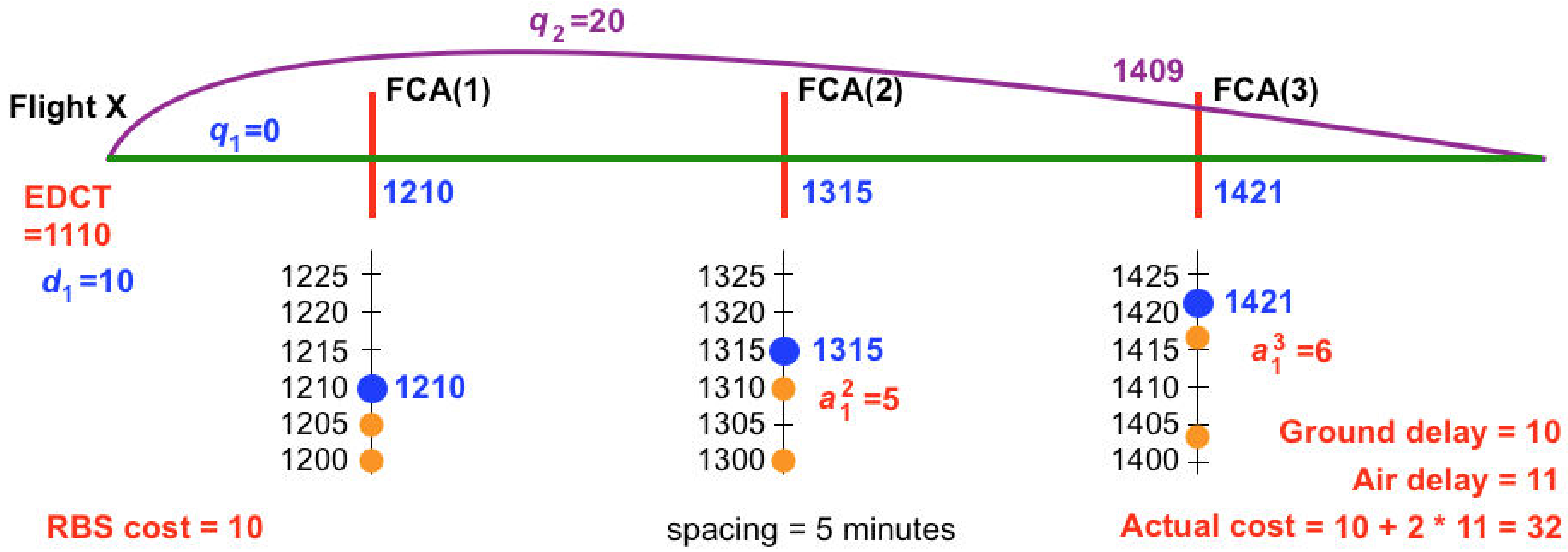

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Mixed-Integer Linear Program (MILP) formulation

$$\min_{\delta,d,a,y} \alpha \sum_{i=1}^{N} c_i + \omega y$$

Input data

N	number of flights
N^A	number of airlines
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If flights i and f cross FCA k within its period of activity, then their ETAs should be separated by at least minimum spacing.

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Ω_{ij}	set of FCAs along route j of flight i

Decision variables

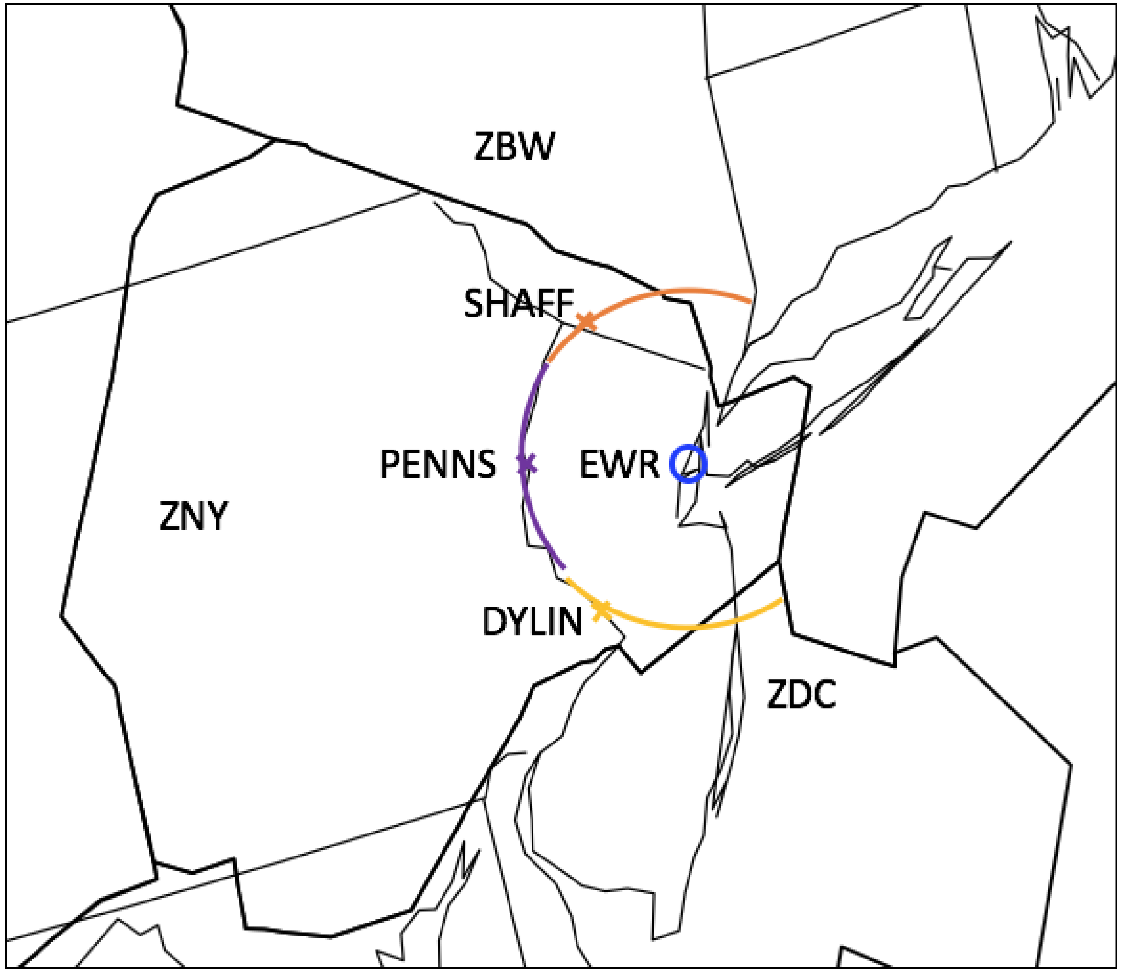
δ_{ij}	$= 1$ if route j is assigned to flight i
d_{ij}	ground delay of flight i on route j
a_{ij}^k	airborne delay of flight i on route j at FCA k
c_i	total cost of route and delay allocation for flight i
y	maximum average airline cost

Test case

- July 14th 2015

Test case

- July 14th 2015
- Four FCAs:
  - Newark Liberty International Airport (EWR)
  - SHAFF (north gate)
  - PENNS (west gate)
  - DYLIN (south gate)
- One hour period of activity
  - 0800Z-0900Z



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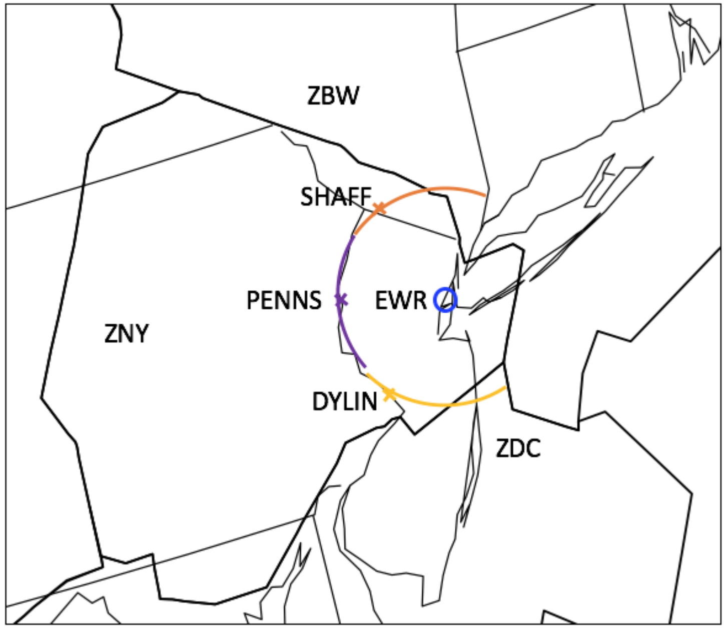
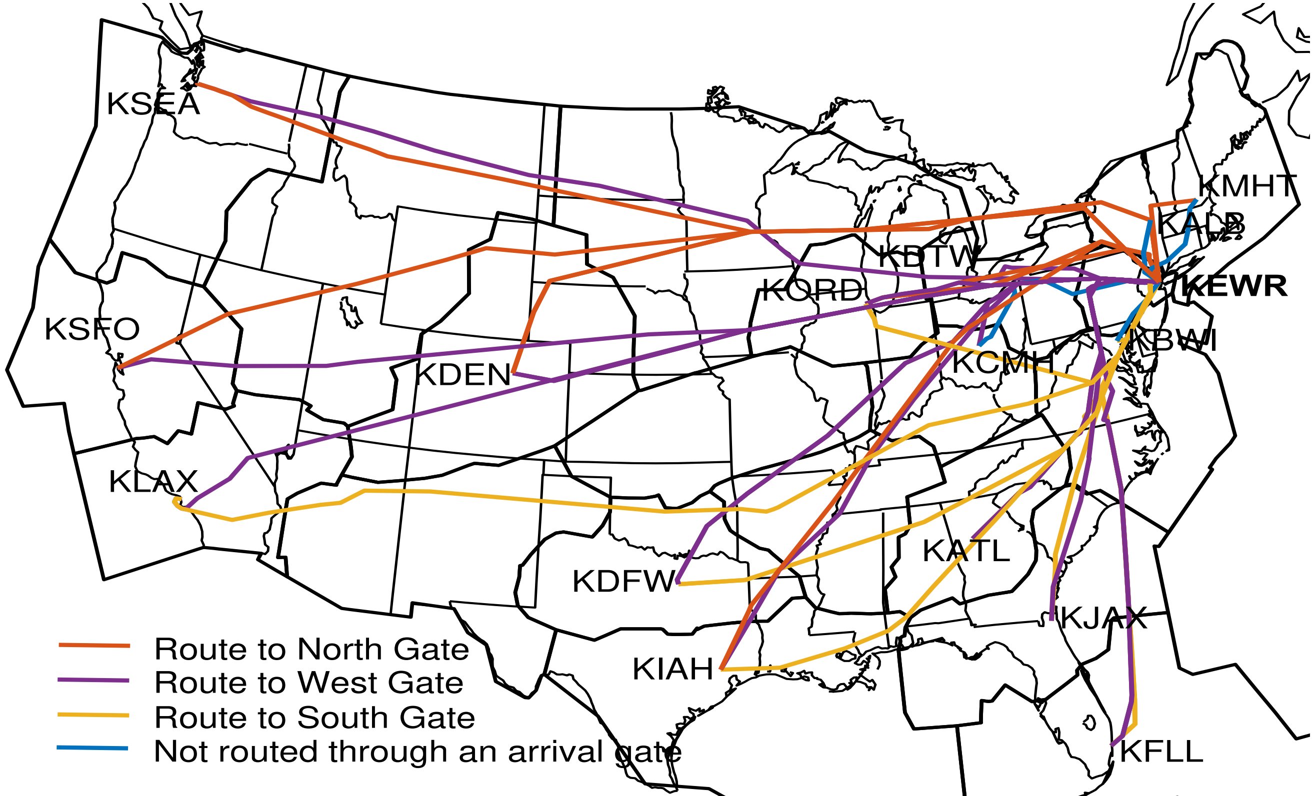
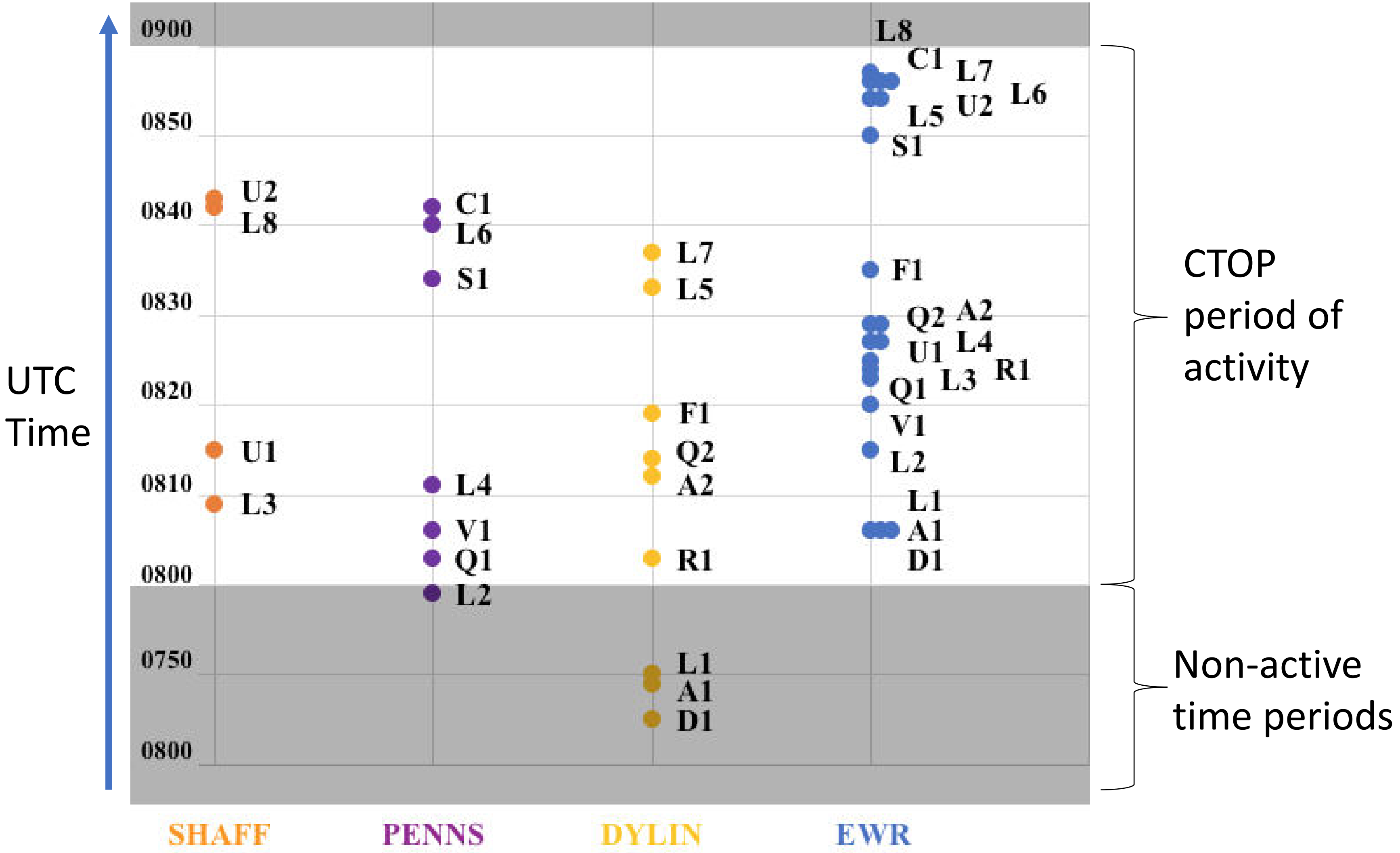
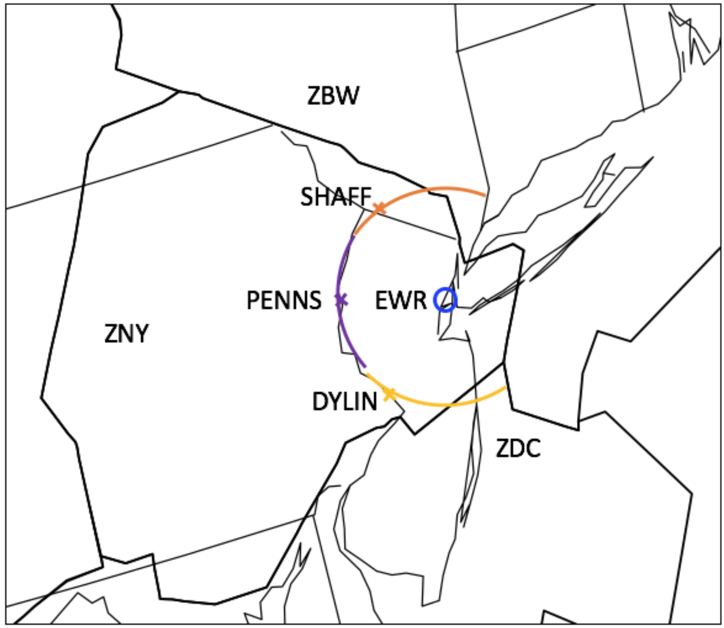
- July 14th 2015
- Four FCAs:
  - Newark Liberty International Airport (EWR)
  - SHAFF (north gate)
  - PENNS (west gate)
  - DYLIN (south gate)
- One hour period of activity
  - 0800Z-0900Z
- 20 flights destined at EWR
  - 2-3 options for each flight
  - FCA crossing times within 0800Z-0900Z





Test case: initial demand





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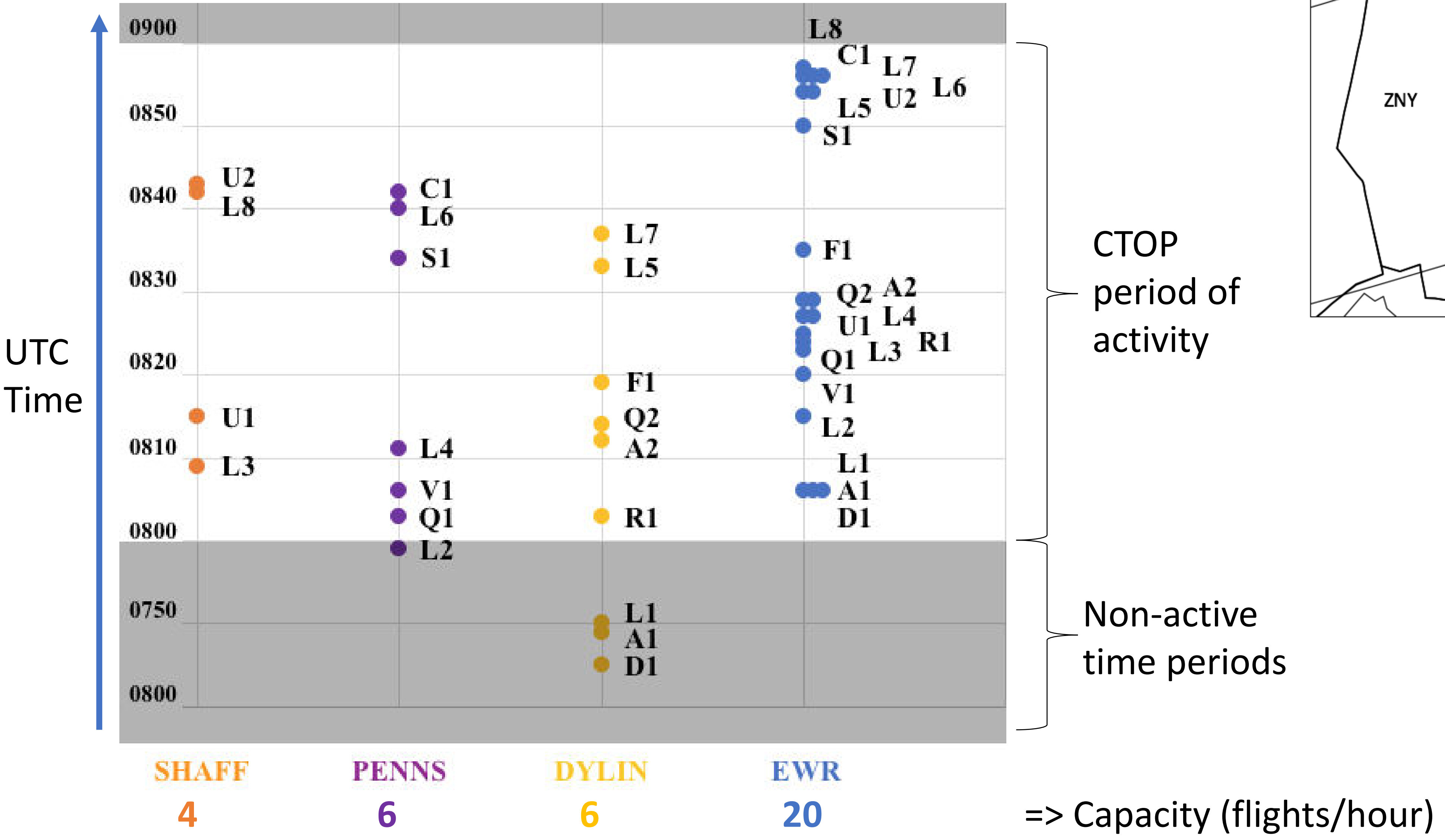

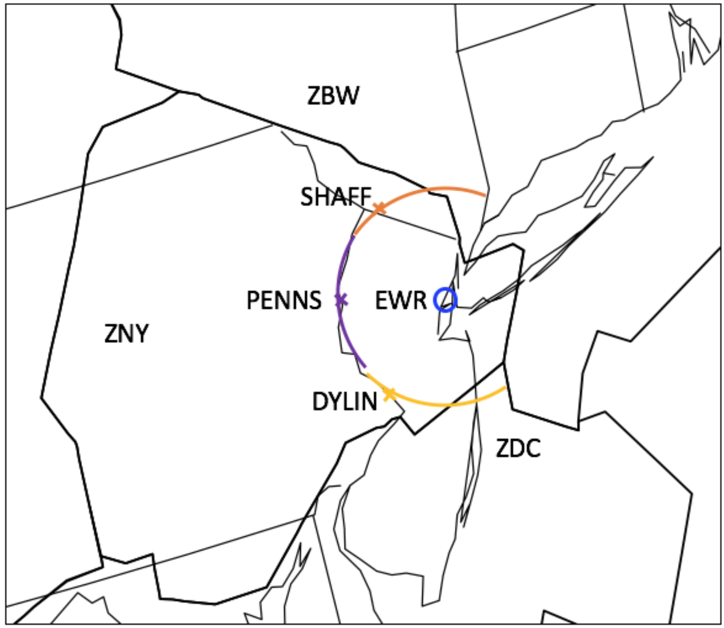

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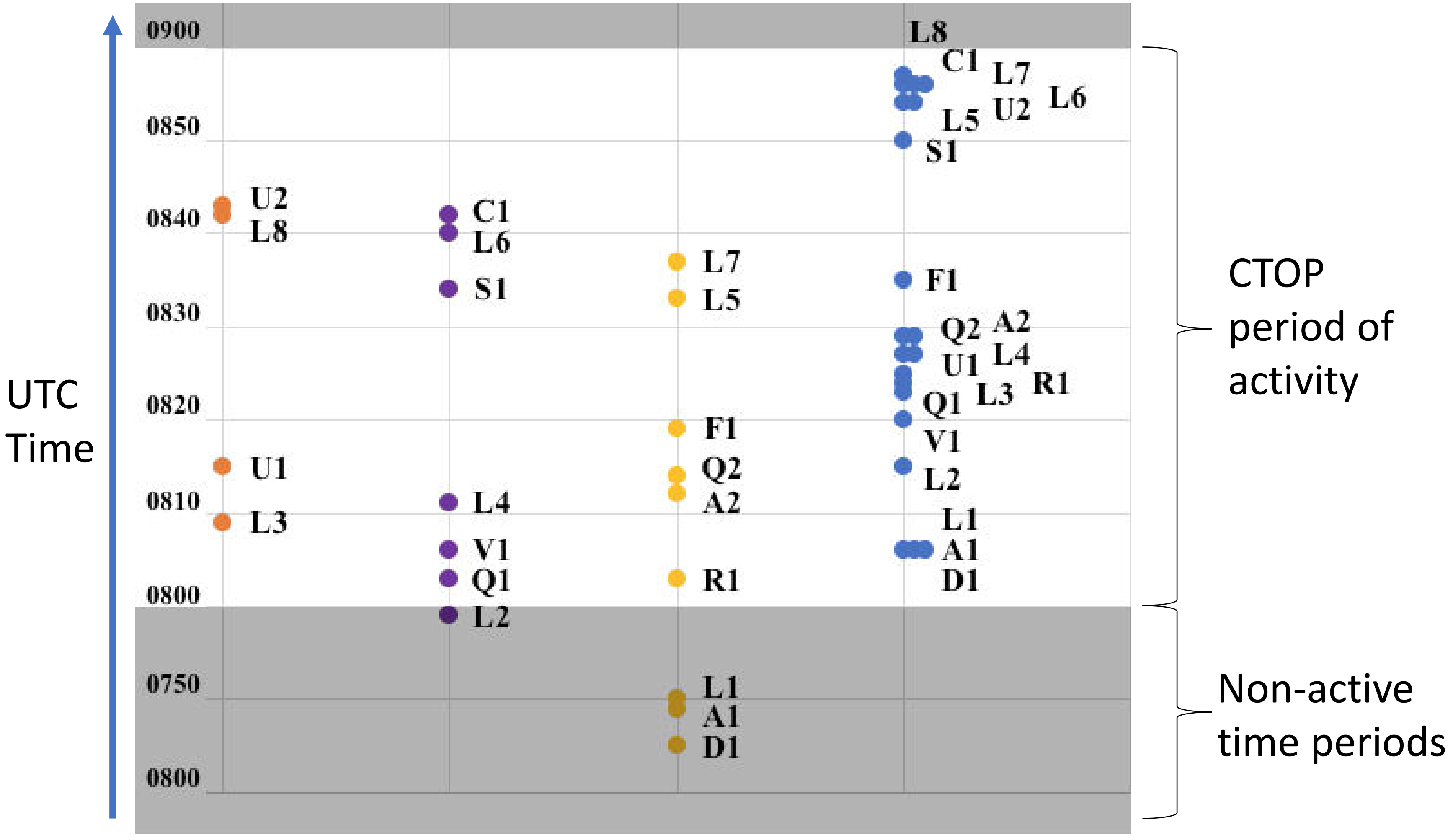

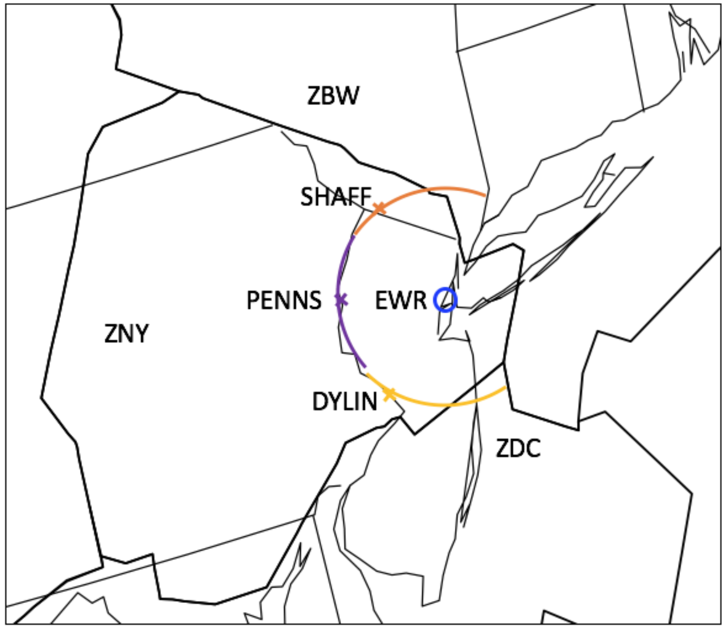

SHAFF	PENNS	DYLIN	EWR	
4	6	6	20	=> Capacity (flights/hour)
15	10	10	3	=> Spacing (minutes)

Efficiency metrics

$$\sum_{flights}\left(RTC + Delay_{ground} + 2\sum_{FCAs} Delay_{air} \right)$$

Estimated cost : cost yielded by the allocation algorithm

Actual cost = Ground cost + Airborne cost

Ground cost = RTC + Ground delay

Airborne cost = 2 x Airborne delay

Efficiency metrics

Actual cost

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Efficiency metrics

Estimated cost (MILP)

=

Actual cost

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Ground cost

=

Estimated cost (RBS)

Airborne cost

Estimated cost	: cost yielded by the allocation algorithm
Actual cost	= Ground cost + Airborne cost
Ground cost	= RTC + Ground delay
Airborne cost	= 2 x Airborne delay

Efficiency of allocation methods

$$\min_{\delta,d,a,y} \alpha \sum_{i=1}^{N} c_i + \omega y$$

	RBS	MILP
	Minutes	
Estimated total cost	143	134
Actual total cost	201	134
Total ground cost	143	120
Total airborne cost	58	14
Maximum flight cost	22	35
Maximum ground delay	20	14
Maximum airborne delay	6	2

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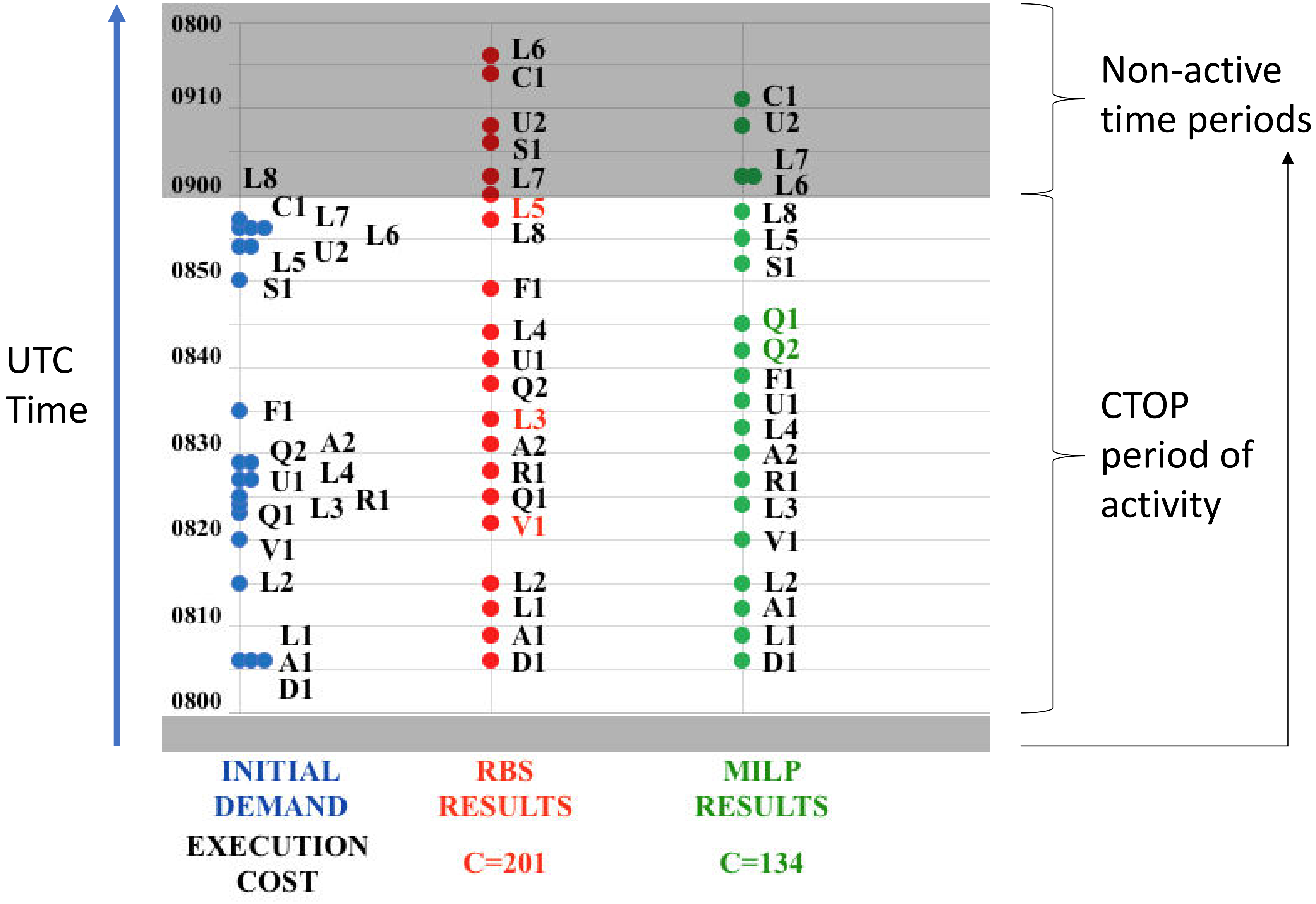
Resulting allocation

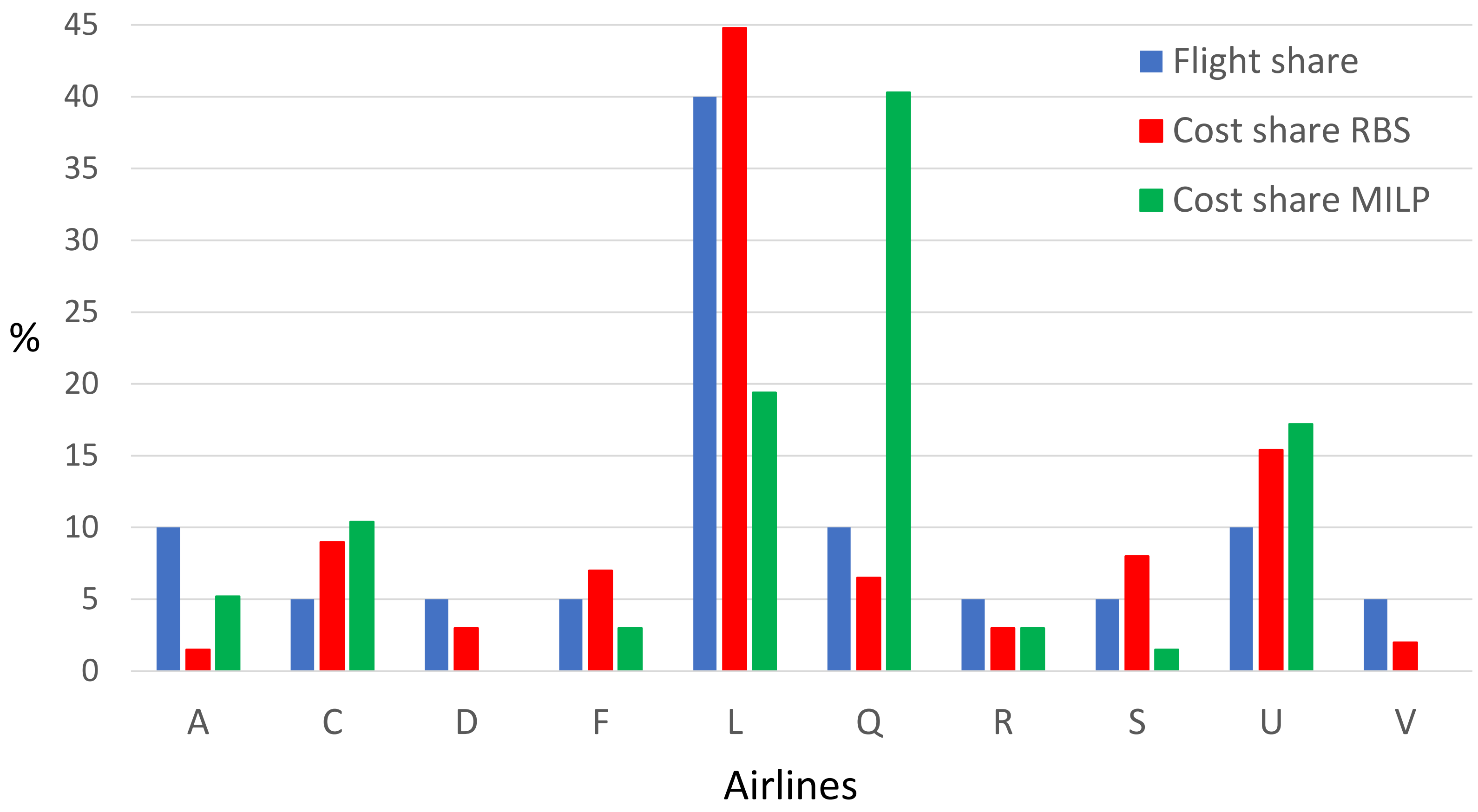
Allocation at EWR

Capacity: 20

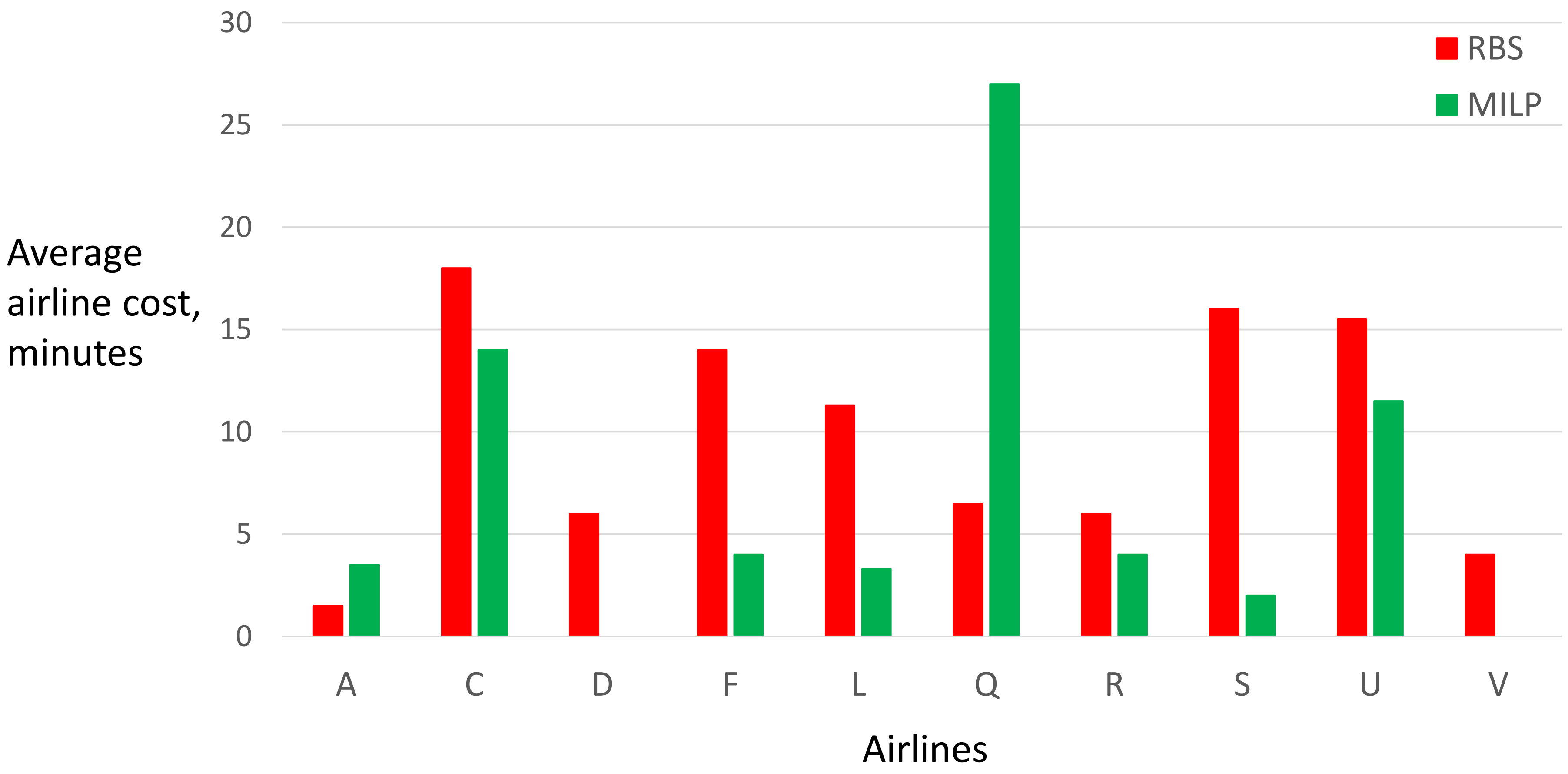
Spacing: 3 minutes



Equity of allocation methods: cost share

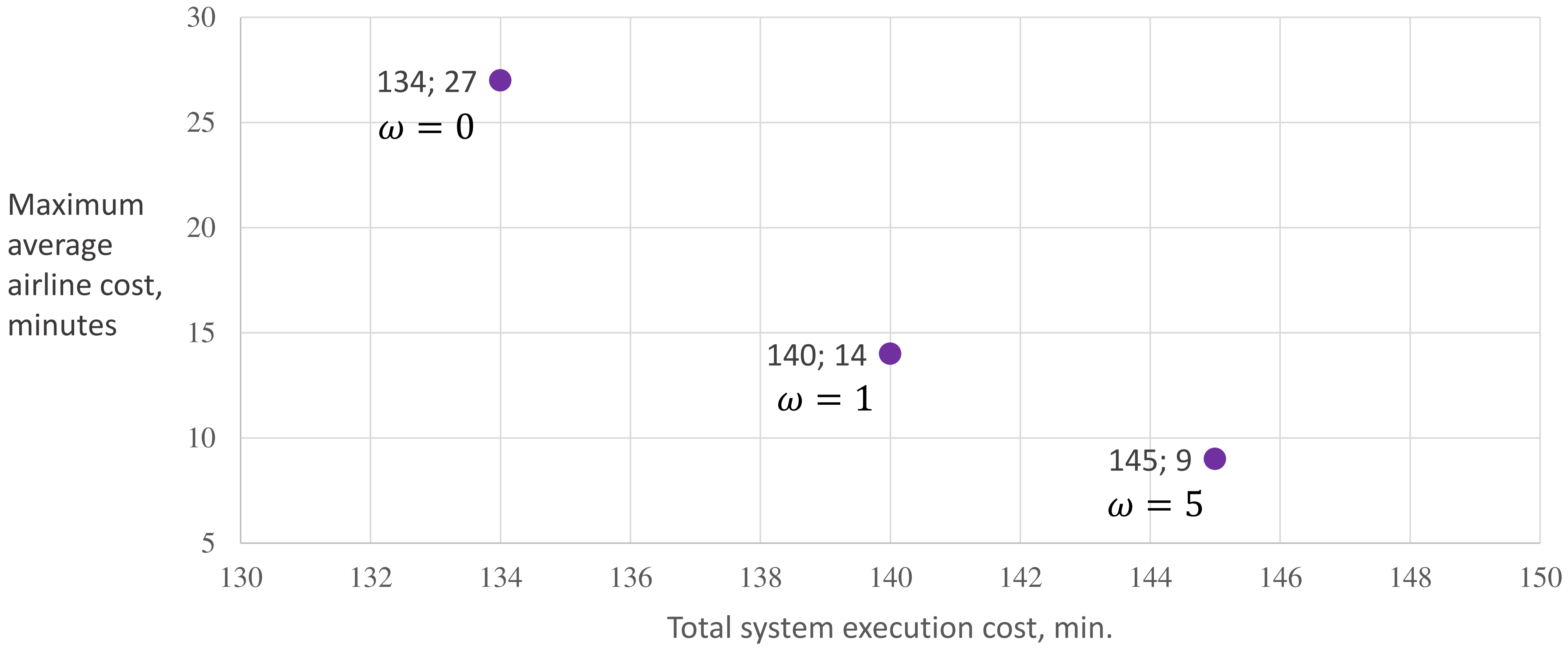


Equity of allocation methods: average airline cost



Efficiency and equity trade-off

$$\min_{\delta,d,a,y} \sum_{i=1}^{N} c_i + \omega y$$



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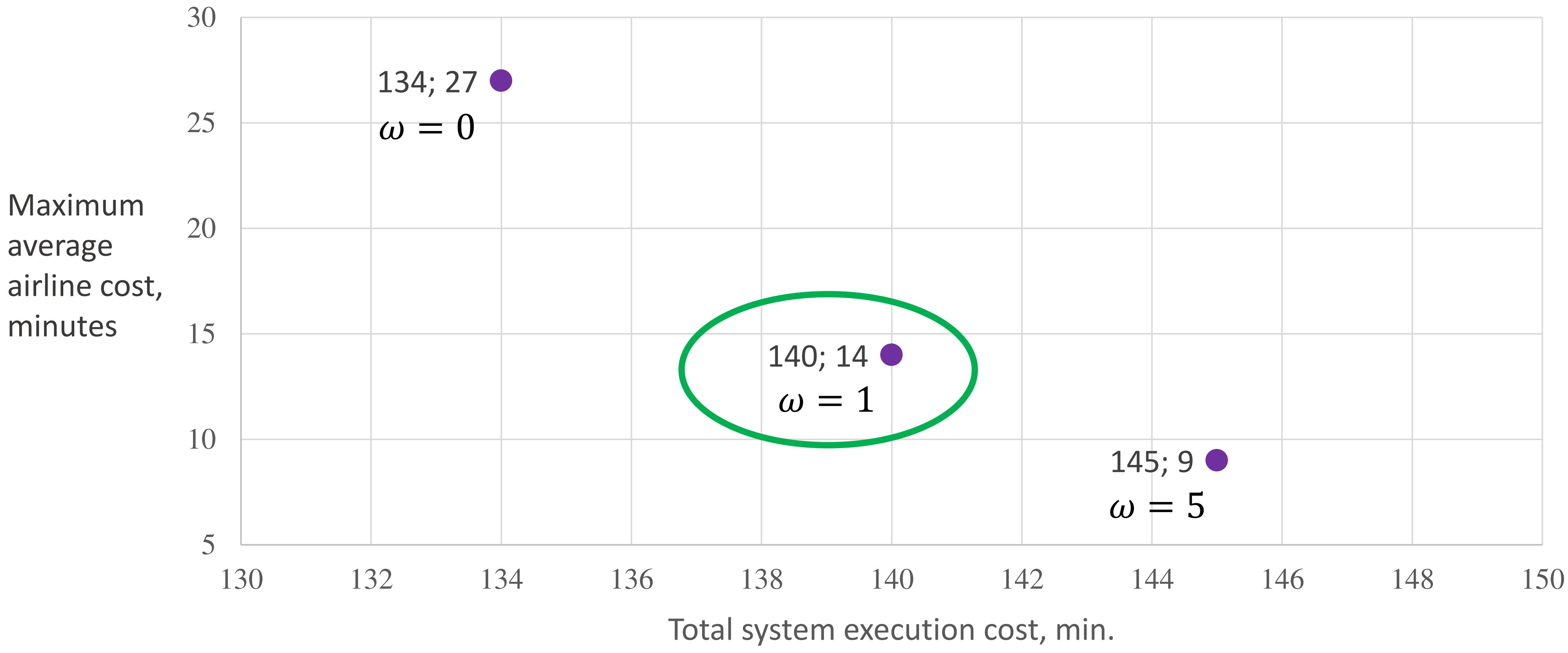
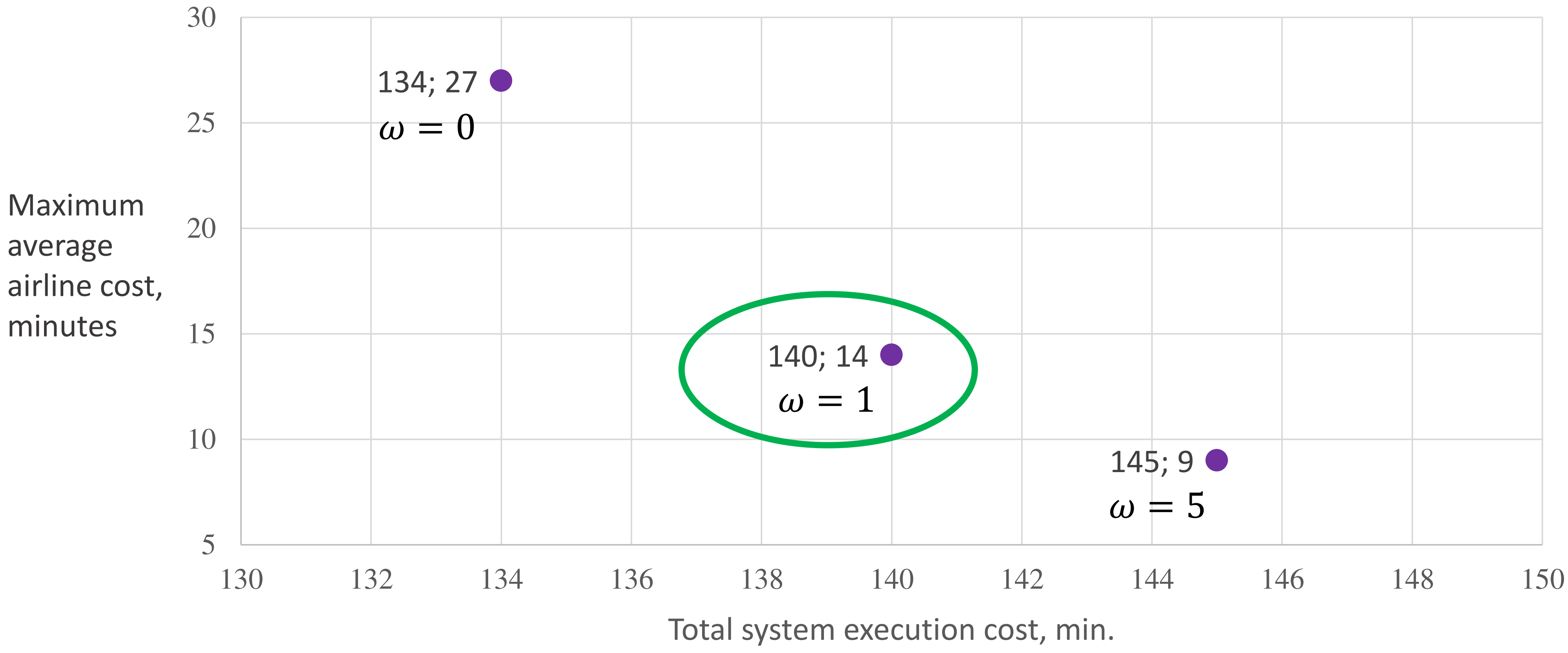


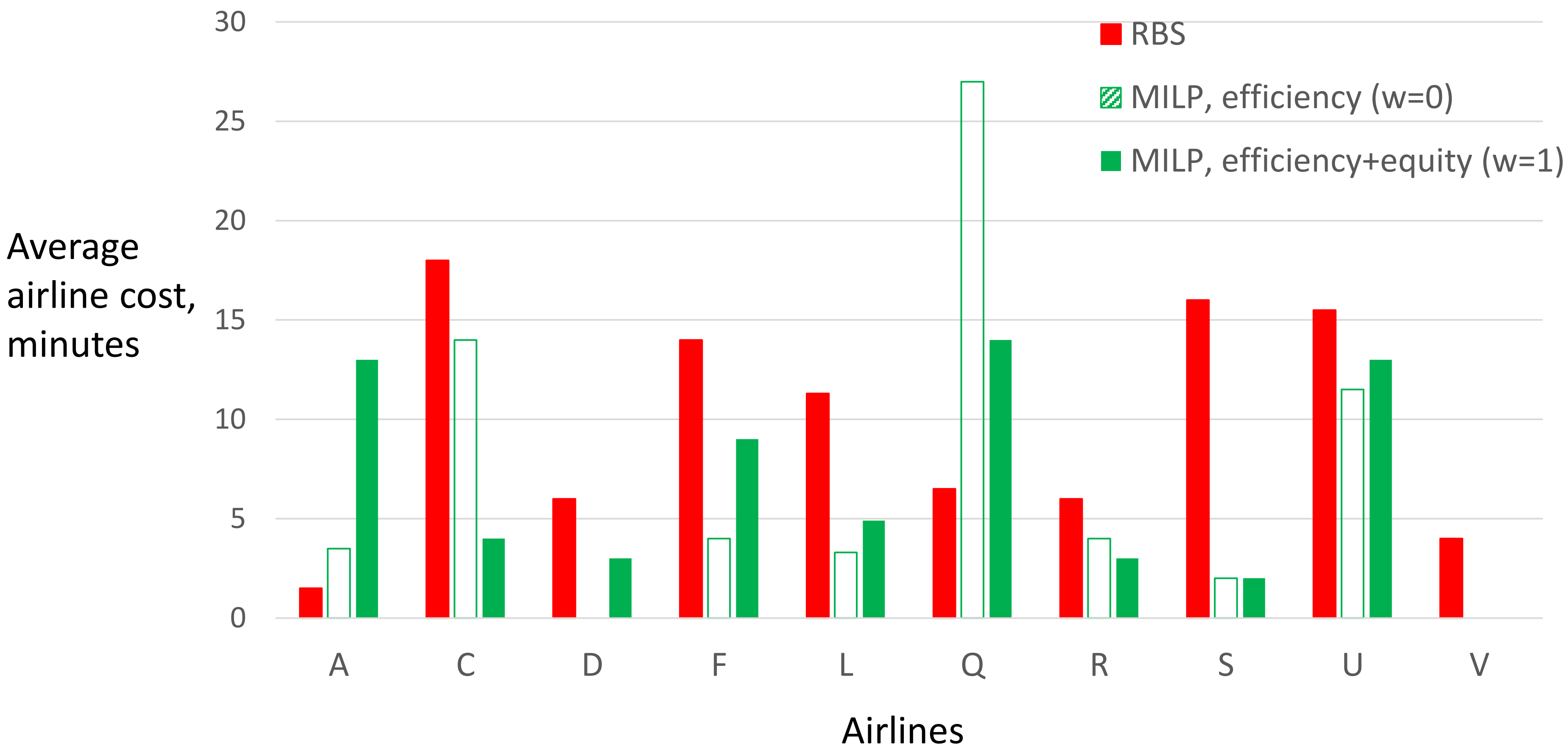
Efficiency and equity trade-off

$$\min_{\delta,d,a,y} \sum_{i=1}^{N} c_i + \omega y$$

RBS:
201, 18



Improved equity: average airline cost



Conclusion

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- Space-based allocation → Uniform flight distribution
- Constraints at multiple FCAs simultaneously → More predictable schedule (in deterministic conditions)
- Global optimization with airborne delays → Improved efficiency compared to RBS
- Equity metric in optimization → Improved equity for airlines

Future work

- Extend to larger test case
  (longer period of activity, more flights)
- Predictability of developed method
  (with demand and capacity uncertainties)
- Stochastic formulation of the optimization problem
- Exempted and pop-up flights

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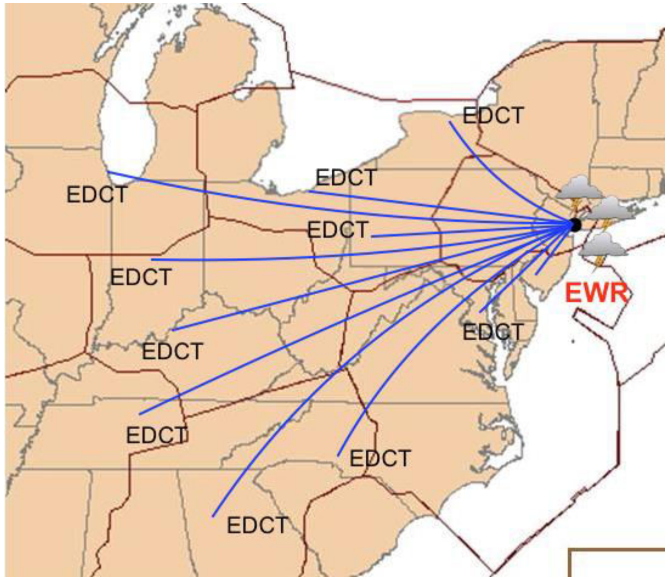
Appendices

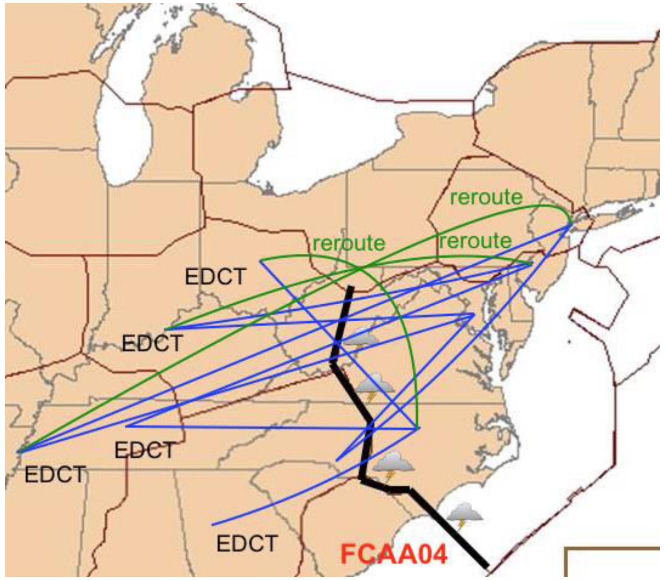
Traffic Management Initiatives (TMIs)

GDP



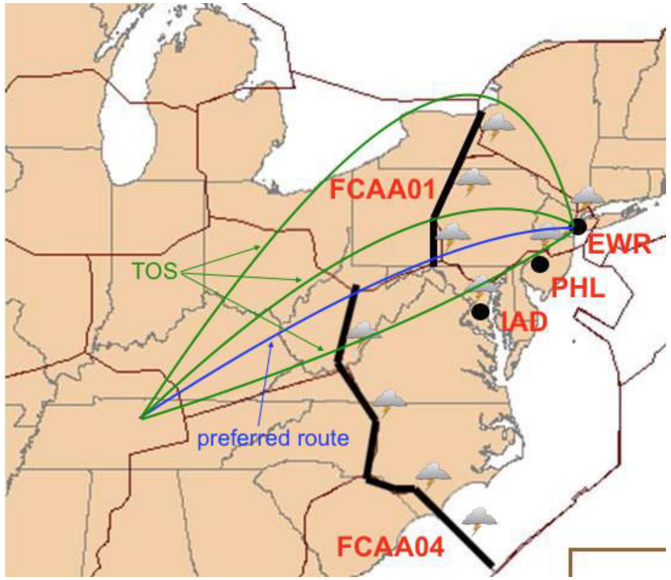
- Arrival airport
- Ground delays =>
  - Expected Departure Clearance Time (EDCT)

AFP



- Flow Constrained Area (FCA)
- Ground delays => EDCTs
- Reroutes
  - Specified by TFM

CTOP (GDP + AFP + CDM)



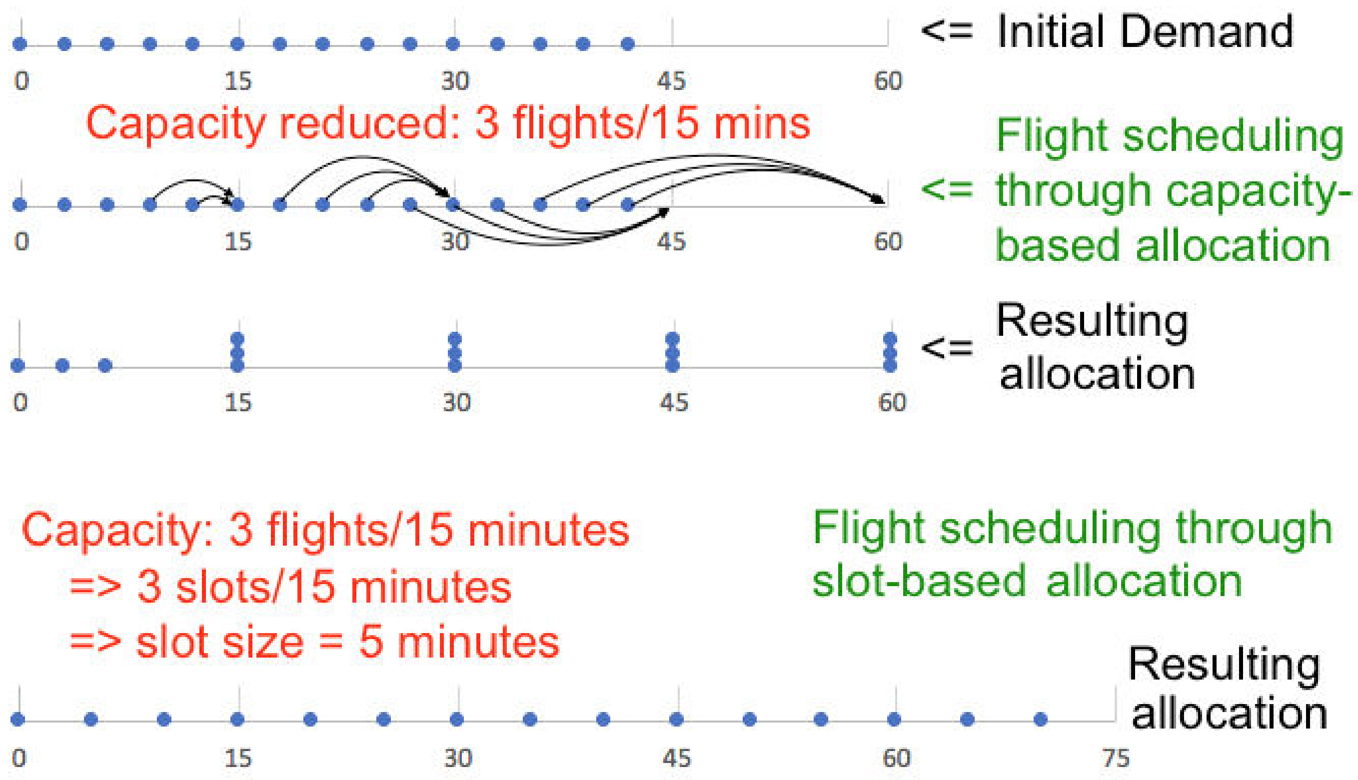
- Multiple FCA and multiple airports
- Ground delays => EDCTs
- Reroutes
  - Trajectory Option Set (TOS) => specified by flight operators

A

Resource allocation problem: overview

- What resources must be allocated?
- What allocation criteria are to be used?
- Which allocation algorithm is to be used?

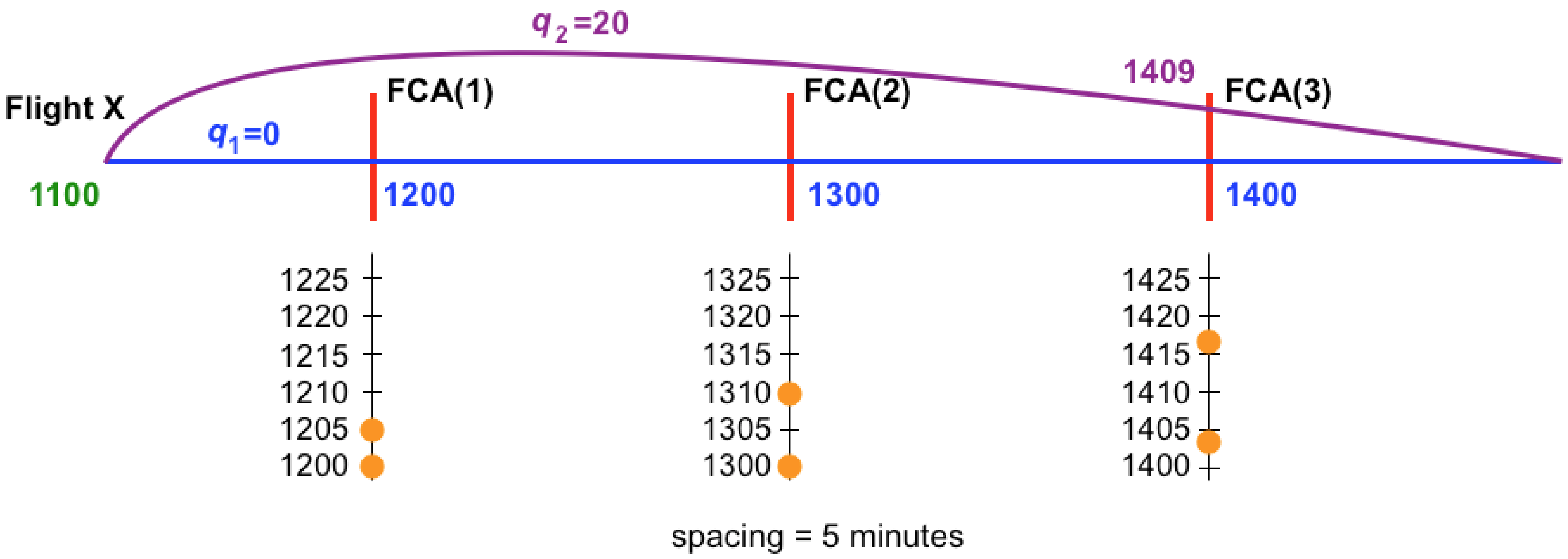
- => FCA capacities
- Capacity-based allocation
  - Sector capacities
- Slot-based allocation
  - GDP, AFP and CTOP
- Space-based allocation
  - MIT, MinIT, TBFM



RBSall: considering all FCAs simultaneously

- For each flight, calculate its Initial Arrival Time (IAT)
  - For each route option from TOS, calculate the Estimated Arrival Time (ETA) at its first (primary) FCA
  - Chose the minimum among these ETAs
- Order flights based on their IATs in a priority list
- For each flight from the priority list, find the best (minimum-cost) available route and delay allocation satisfying the spacing constraints at all FCAs along this route at the same time

RBSall scheduling example



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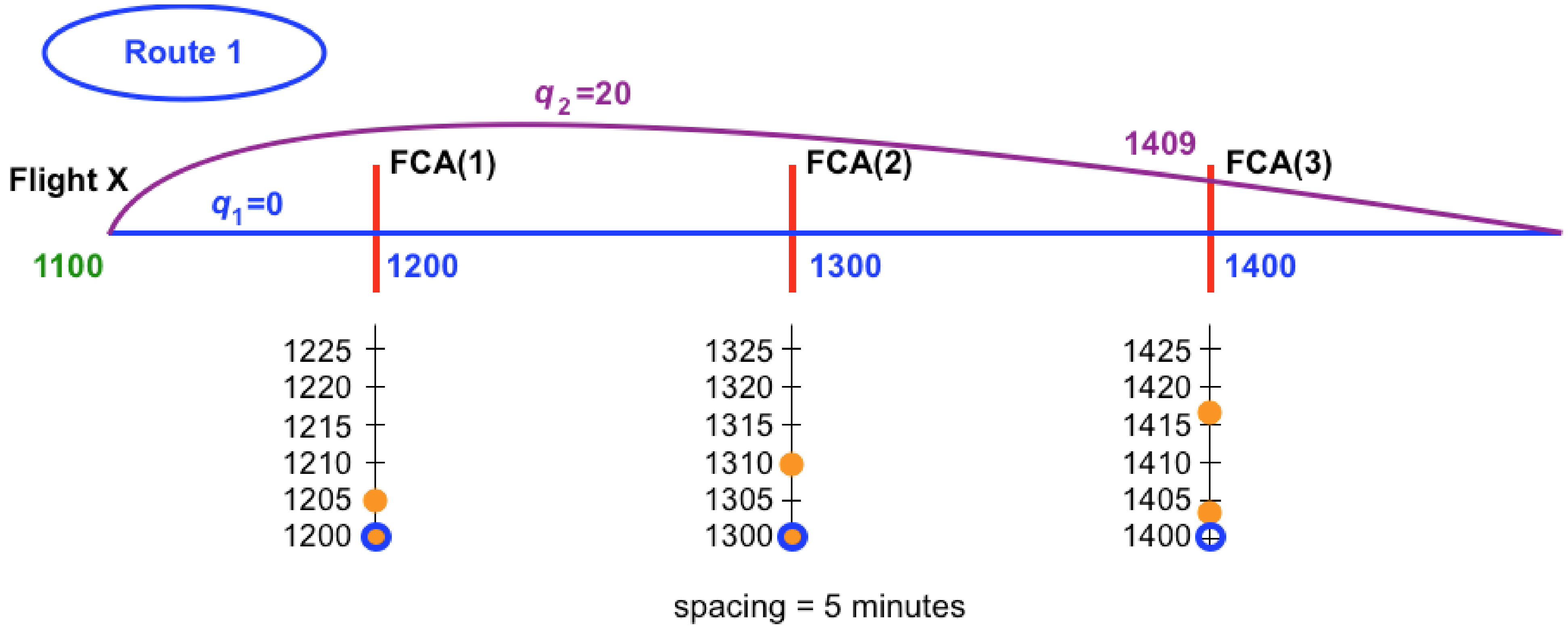
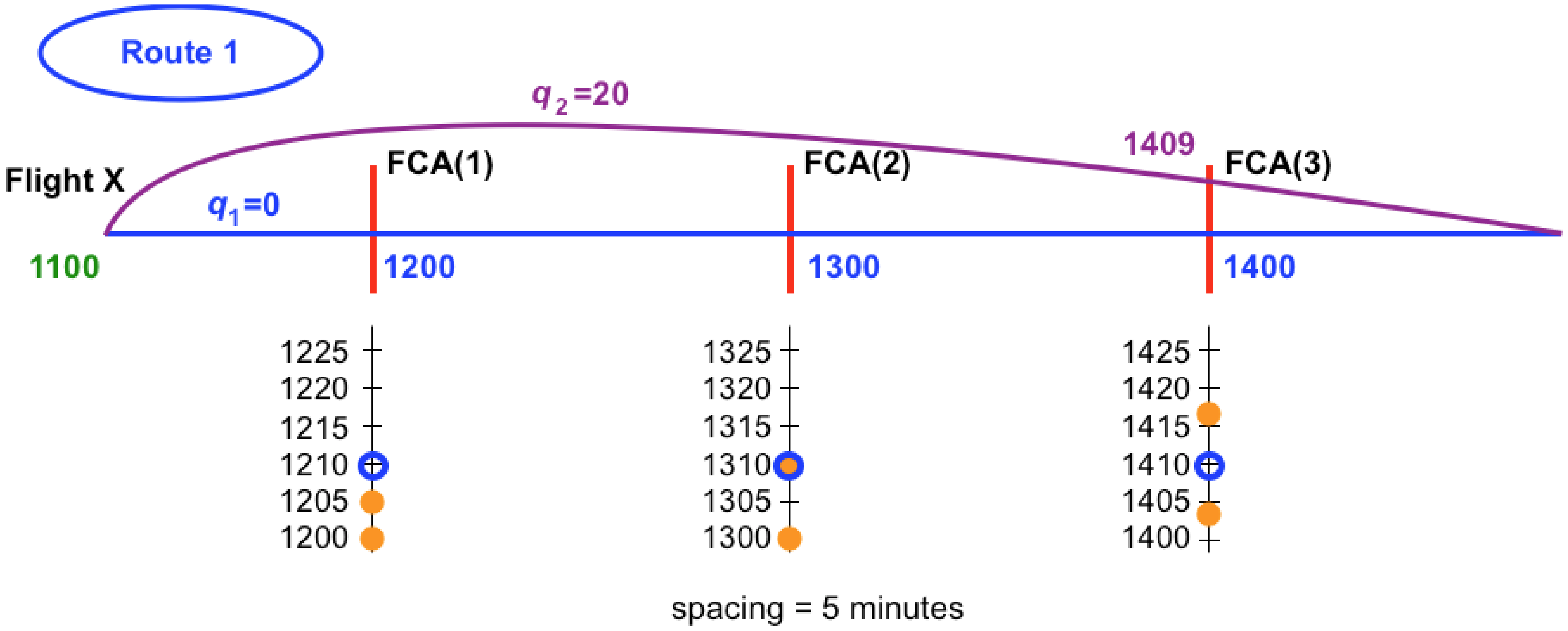


D

RBSall scheduling example



D

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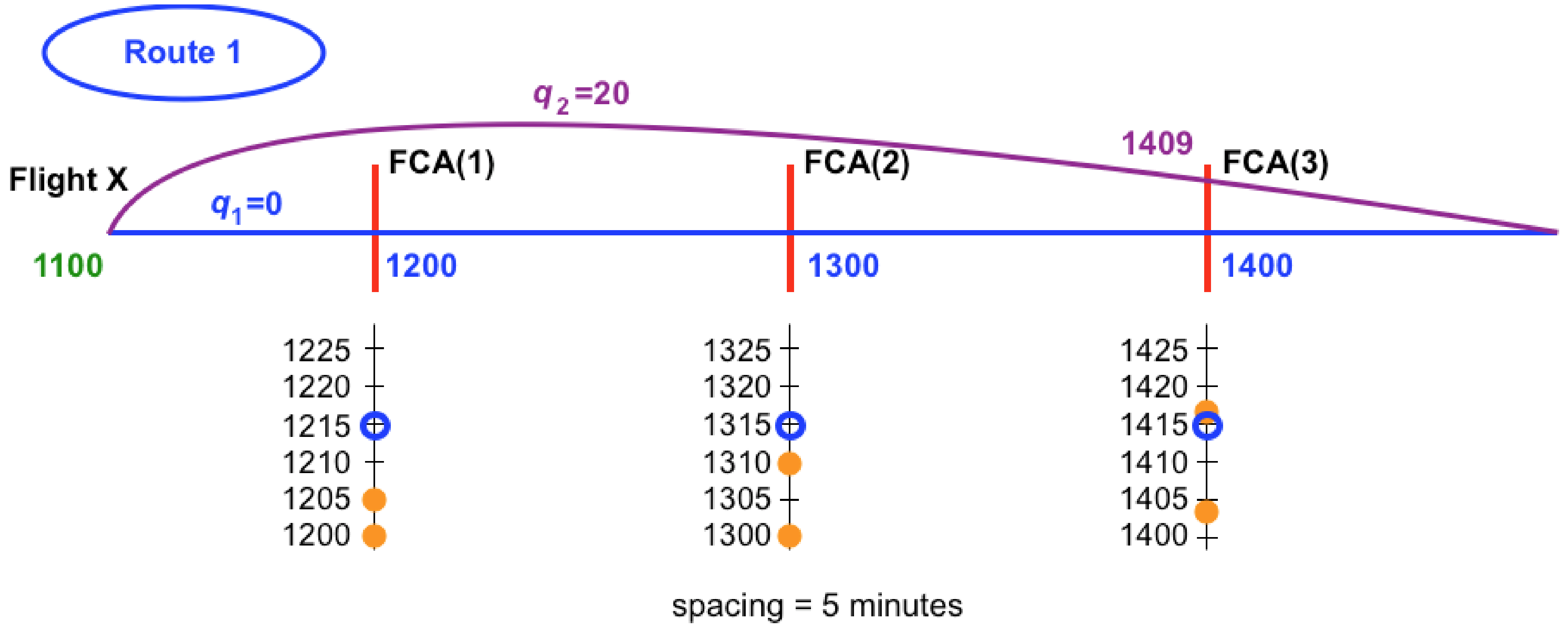

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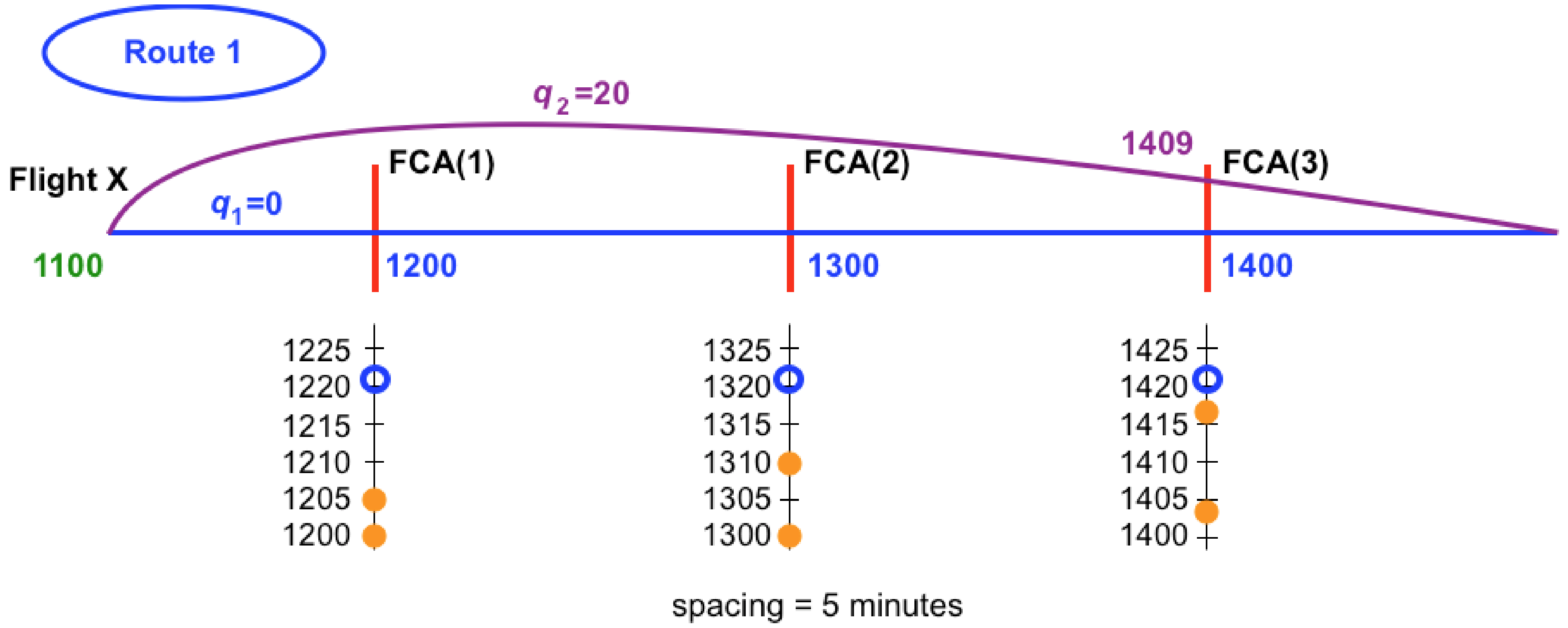

D

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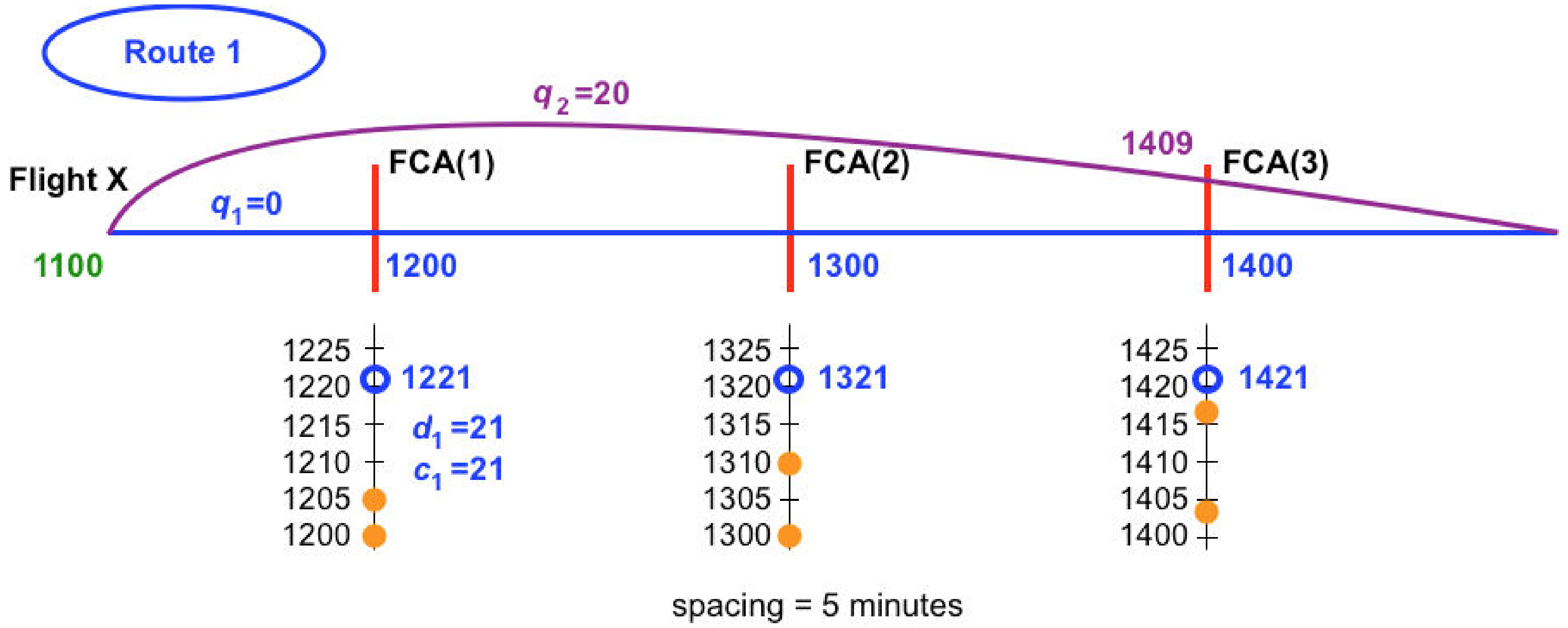

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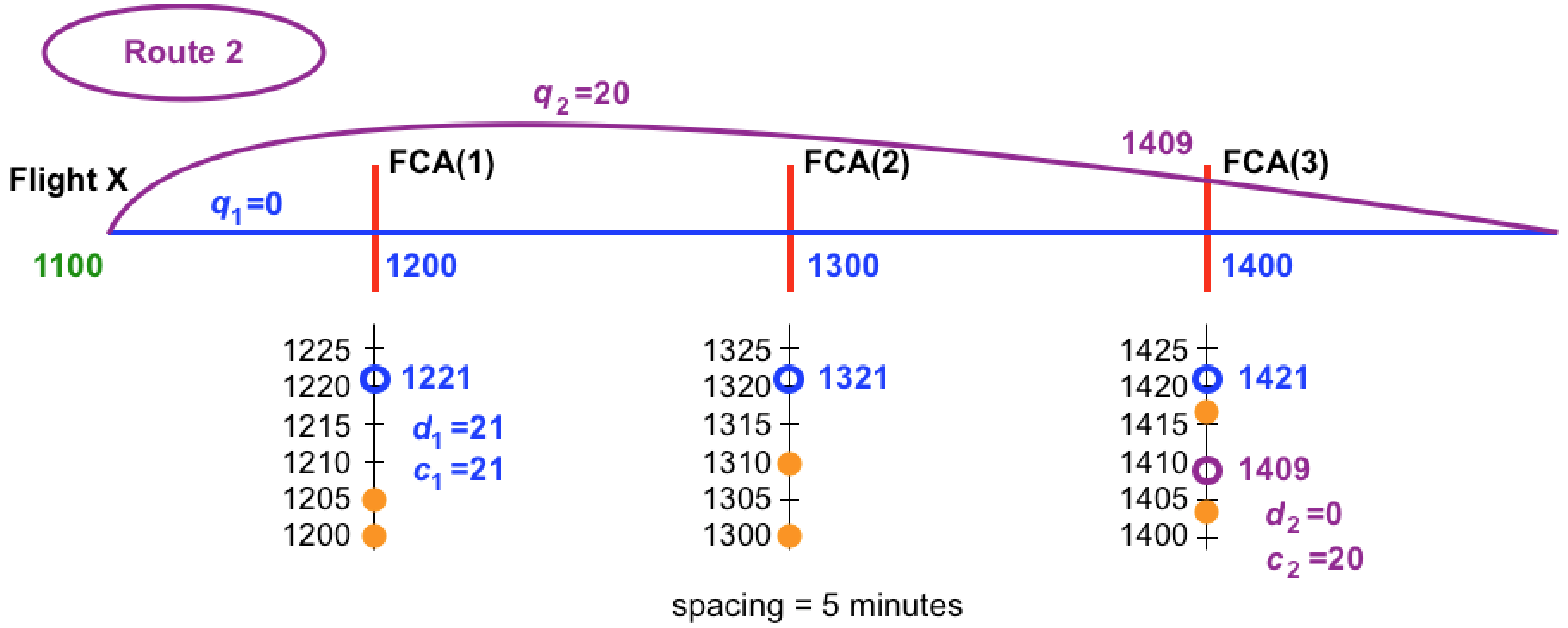

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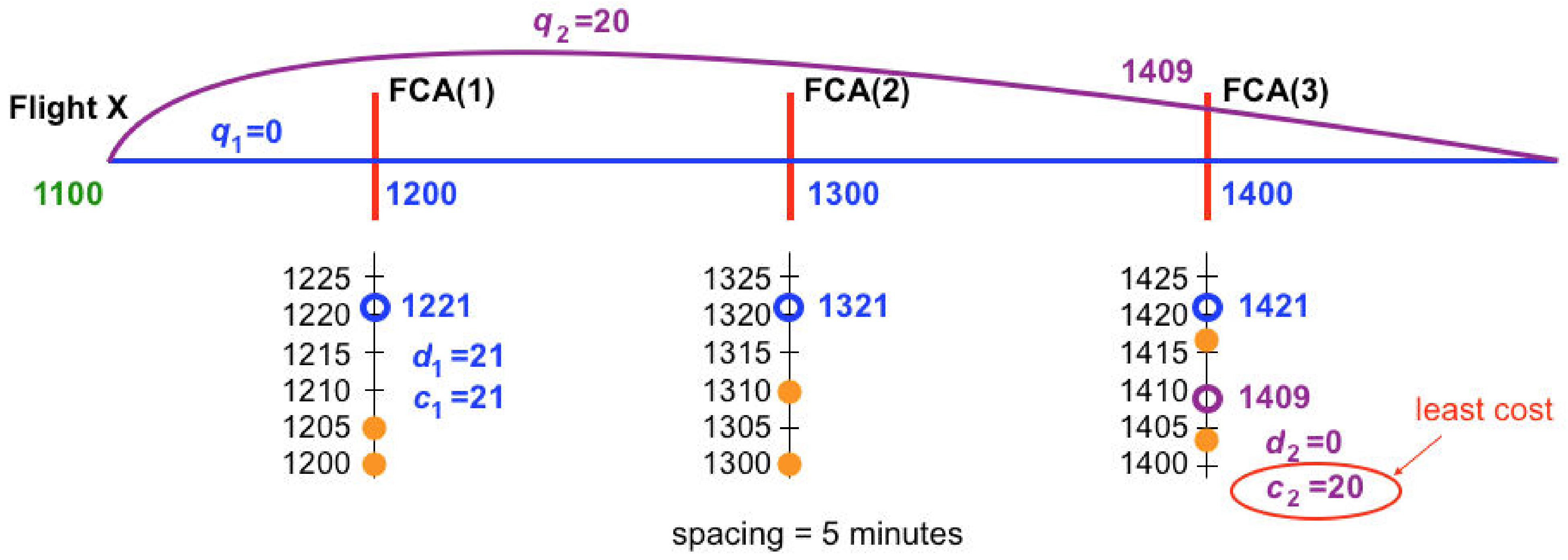

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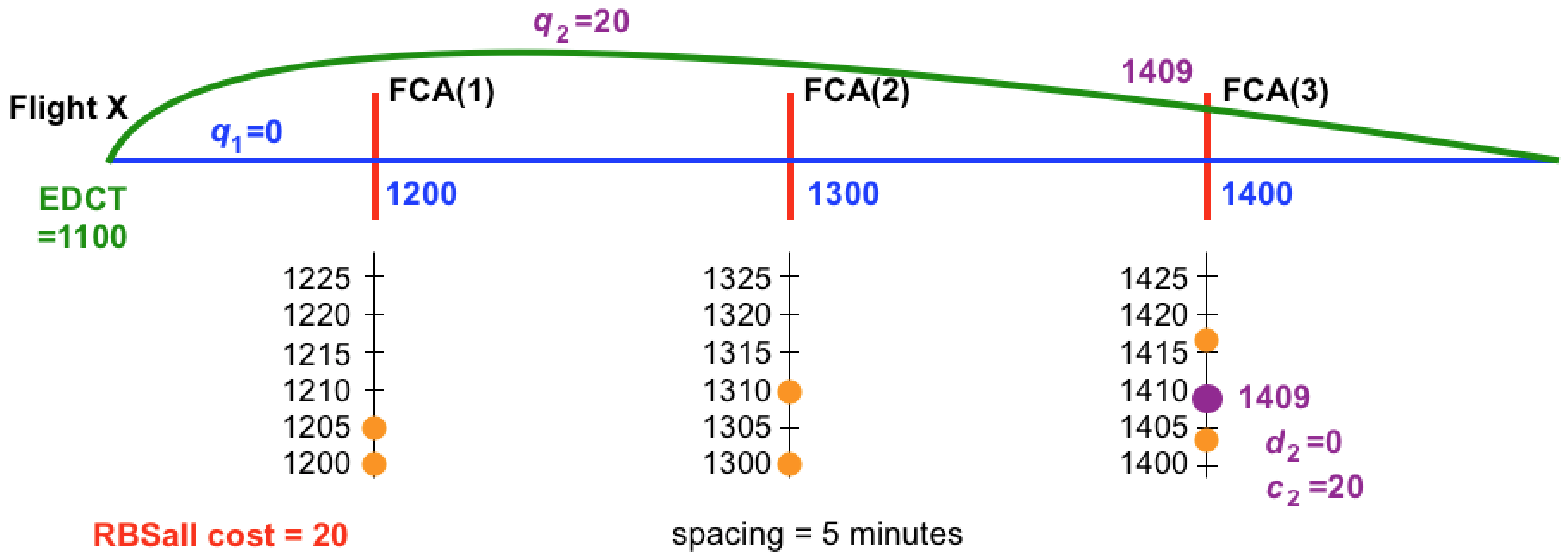

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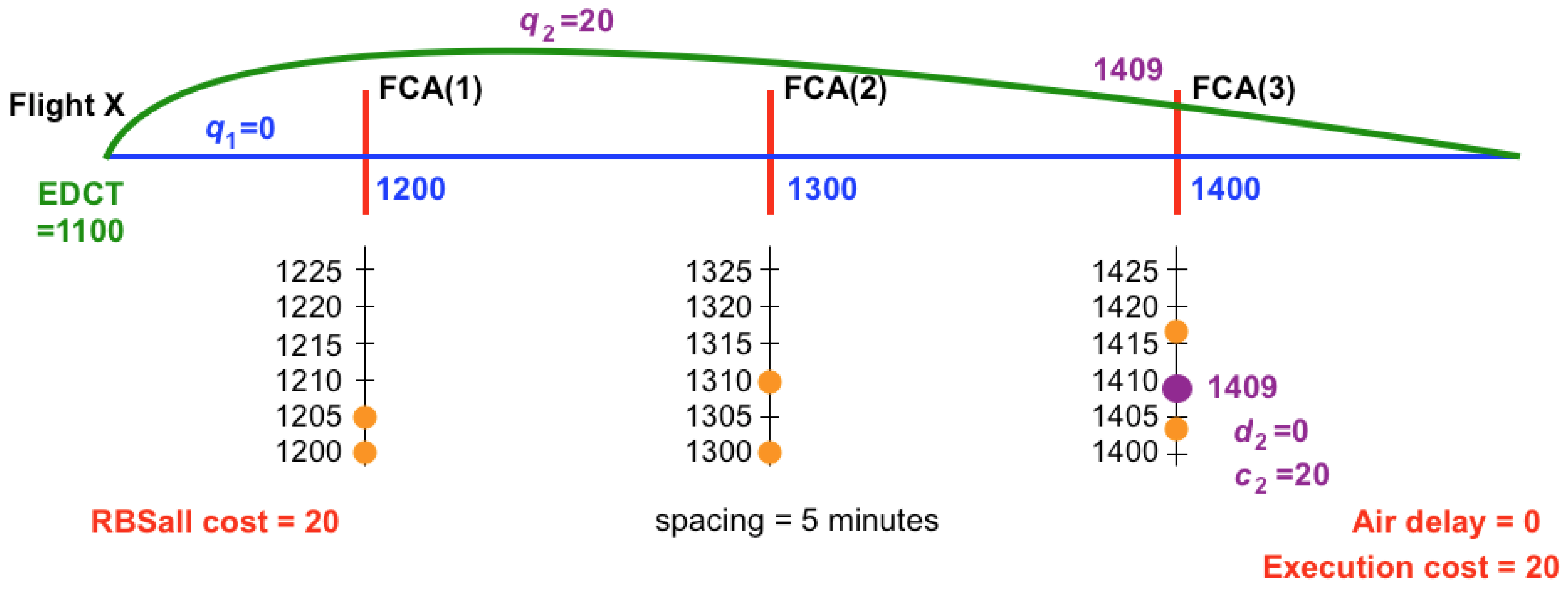

D

MILP formulation: full

$$\min_{\delta,d,a,y} \alpha \sum_{i=1}^{N} c_i + \omega y$$

$$\text{s.t. } c_i = \sum_{j=1}^{N_i} \left(\beta q_{ij}\delta_{ij} + d_{ij} + \gamma \sum_{h=2}^{H_{ij}} a_{ij}^{k_{ij}^h} \right)$$

$$d_{ij} + \sum_{h=2}^{H_{ij}} a_{ij}^{k_{ij}^h} \leq M\delta_{ij}$$

$$\tau_i^k = \sum_{j\in\Phi_i^k} \left(t_{ij}^k \delta_{ij} + d_{ij} + \sum_{m\in\Omega_{ij};\, 2\leq \mathrm{id}(m)\leq \mathrm{id}(k)} a_{ij}^m \right)$$

$$M\nu_{i,f}^k + \tau_i^k - \tau_f^k \geq \sum_{l=0}^{L^k+1} \frac{S^{k,l}}{2}\left(x_i^{k,l} + x_f^{k,l}\right)$$

$$M\left(1-\nu_{i,f}^k\right) + \tau_f^k - \tau_i^k \geq \sum_{l=0}^{L^k+1} \frac{S^{k,l}}{2}\left(x_i^{k,l} + x_f^{k,l}\right)$$

$$y \geq \frac{1}{N^u} \sum_{i\in\Lambda^u} c_i$$

$$\sum_{j=1}^{N_i} \delta_{ij} = 1$$

$$\tau_i^k \geq \sum_{l=0}^{L^k+1} S^{k,l} x_i^{k,l}$$

$$\tau_i^k < \sum_{l=0}^{L^k+1} E^{k,l} x_i^{k,l}$$

$$\sum_{l=0}^{L^k+1} x_i^{k,l} \leq 1$$

$$y, d_{ij}, a_{ij}^k \geq 0$$

$$a_{ij}^k \leq A_{ij}^k$$

$$\delta_{ij}, x_i^{k,l}, \nu_{i,f}^k \in \{0,1\}$$

$$i = 1, \dots, N$$

$$j = 1, \dots, N_i$$

$$k = 1, \dots, Z$$

$$l = 0, \dots, L^k + 1$$