Scheduling Aircraft Landings to Closely Spaced Parallel Runways

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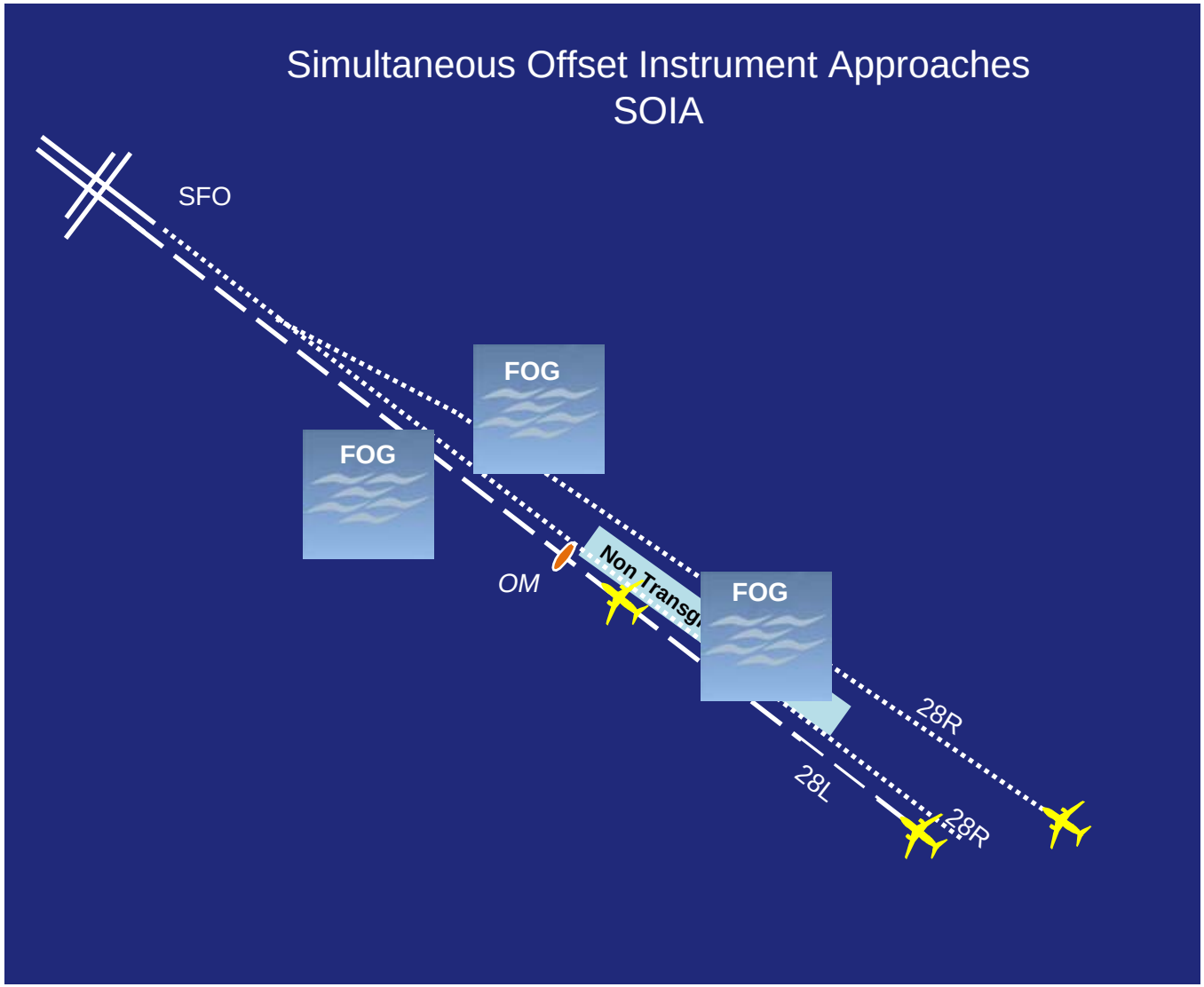

Simultaneous Offset Instrument Approaches
SOIA
SFO
FOG
FOG
FOG
OM
Non Transg
28R
28L
28R

Objective:

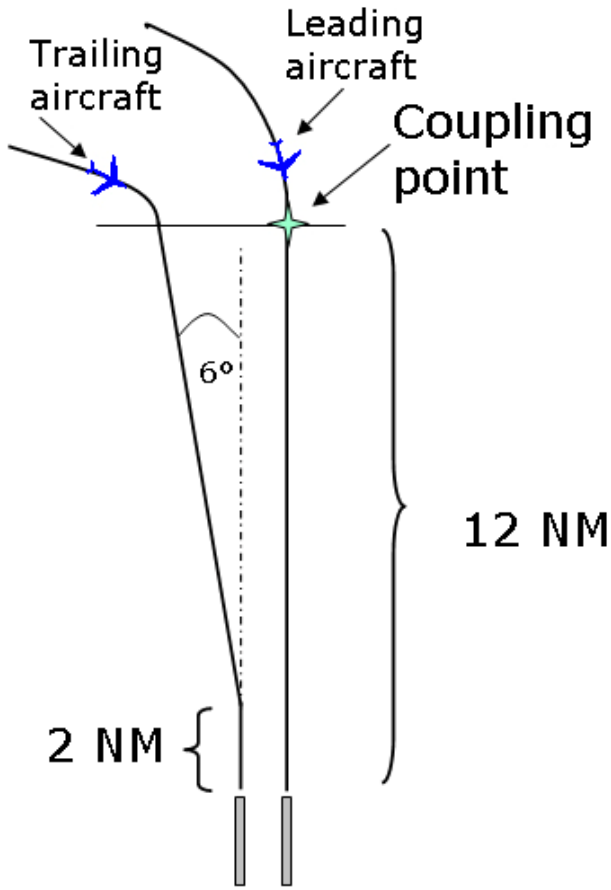
- Development of a scheduling model for very closely spaced parallel approaches
- Investigation of the merits of various scheduling methods
- Throughput increase of ~ 5-10% over first-come-first-served scheduling with pairing

Scope:

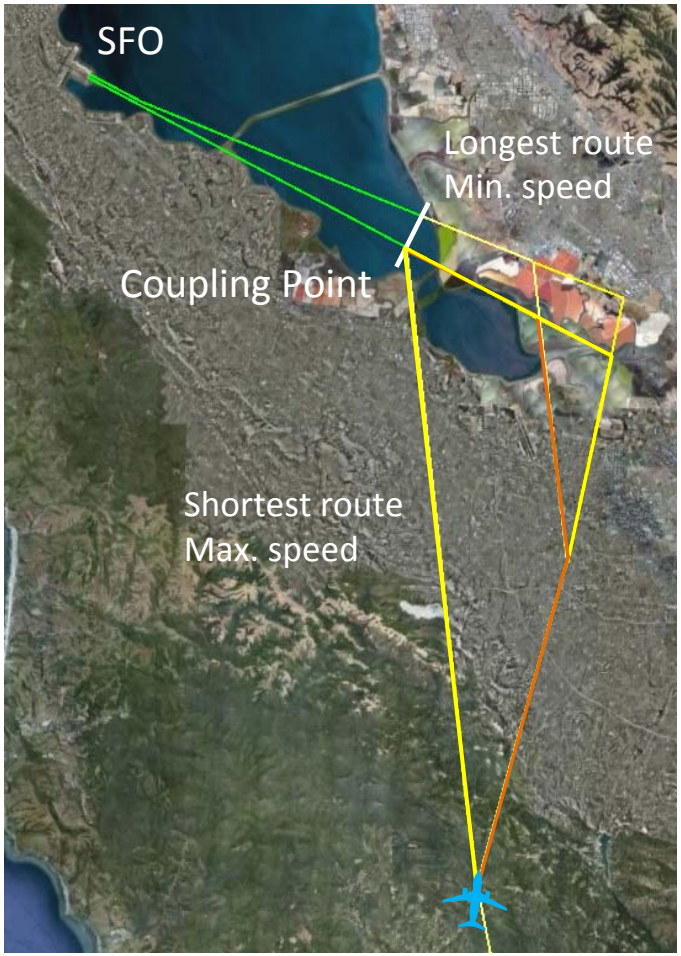
- First-come-first-served: with/without pairing allowed
- Genetic algorithm: with/without greedy algorithm
- Mixed integer linear program
- Model based on Terminal Area Capacity Enhancement Concept

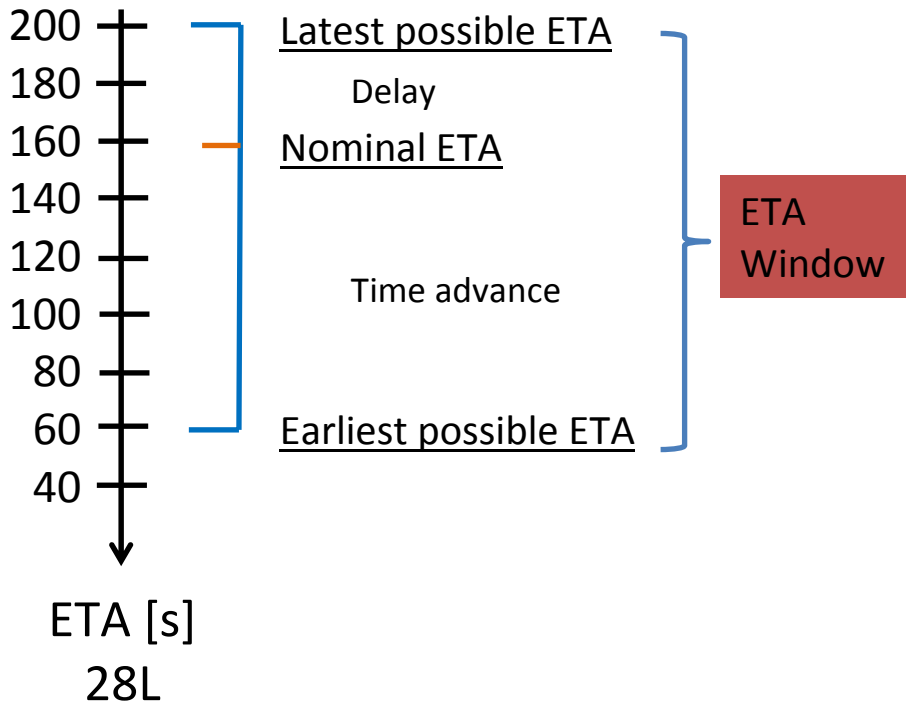
Methodology:

- Input: earliest and latest possible arrival time of aircraft
- Objective: minimize arrival time at coupling point of last aircraft in set (i.e. makespan)
- Constraints: temporal, pairing, sequencing, separation, route and grouping



Temporal constraints:

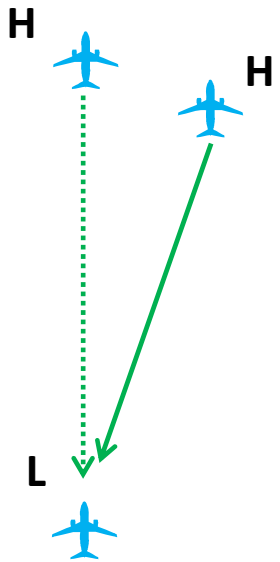


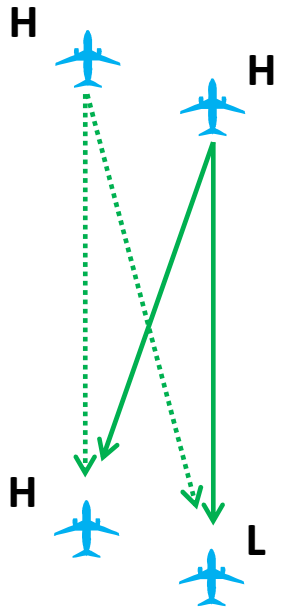


Pairing constraints:

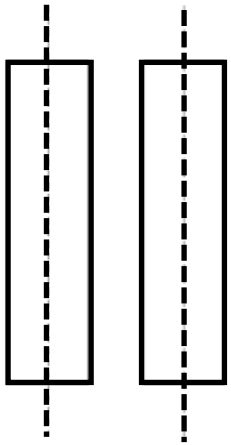
Sequencing constraint:

Separation constraint:

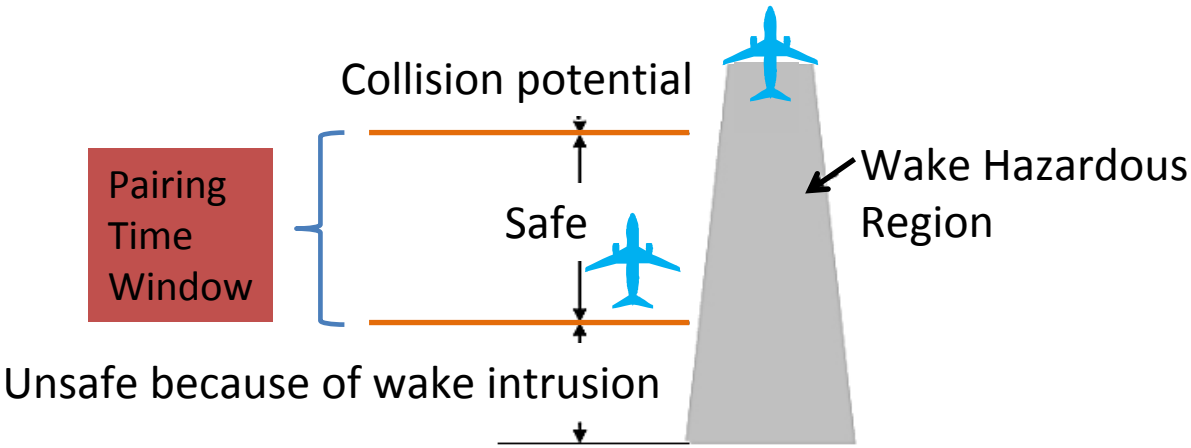




Separation constraint:



Very Closely Spaced
Parallel Runways



Precedence constraint:

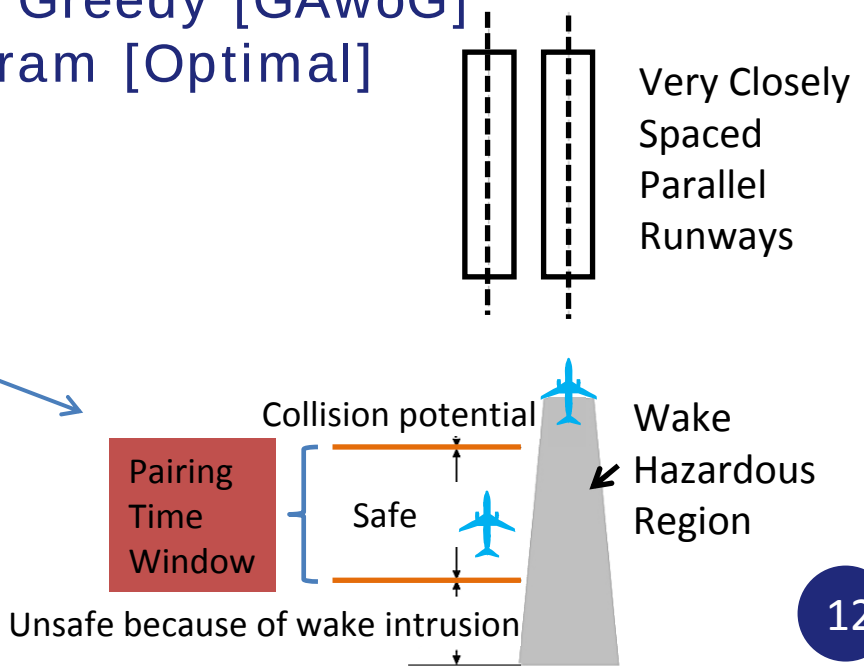
- From same route + paired: change of sequence is ok
- From same route + not paired: change of sequence is not ok

Grouping constraint:

A/C Type	Group #	A/C Type	Group #
A300	A	BE20	B
A310	A	C560	B
A320	A	F28	B
A340	A	B707	C
B727	A	C130	C
B73A	A	C550	C
B73C	A	CARJ	C
B74A	A	CL60	C
B757	A	F100	C
B767	A	F900	C
B777	A	FA10	C
DC10	A	FA20	C
DC8	A	FA50	C
DC9	A	H25B	C
L101	A	LJ35	C
MD11	A	C421	D
MD80	A	BA46	E

Independent Variables:

- Scheduling method:
  - FCFS with pairing [FCFSwP]
  - FCFS without pairing [FCFSwoP]
  - Genetic Algorithm with Greedy [GAwG]
  - Genetic Algorithm without Greedy [GAwoG]
  - Mixed Integer Linear Program [Optimal]
- Pairing Time Window:
  - 5-10 sec
  - 5-15 sec
  - 5-20 sec
- ETA window:
  - -60–600 sec
  - -60–1200 sec
  - -60–1800 sec



Dependent Variables:

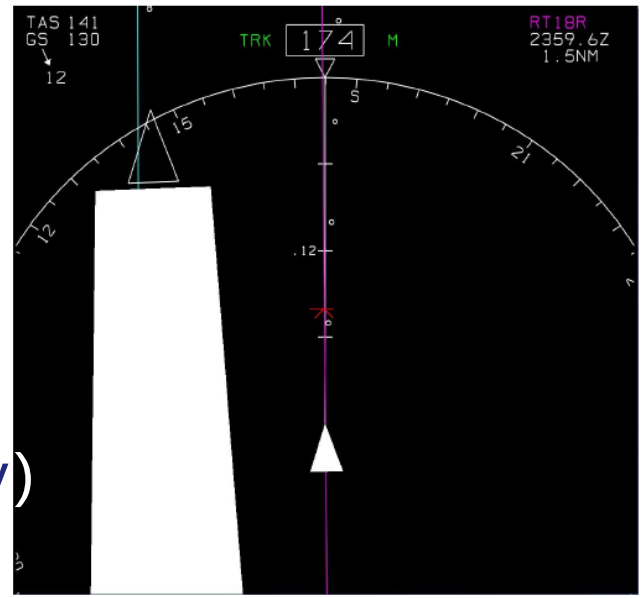
- Makespan (throughput)
- Average delay
- Computation time
- Number of pairs in schedule
- Actual spacing between paired aircraft

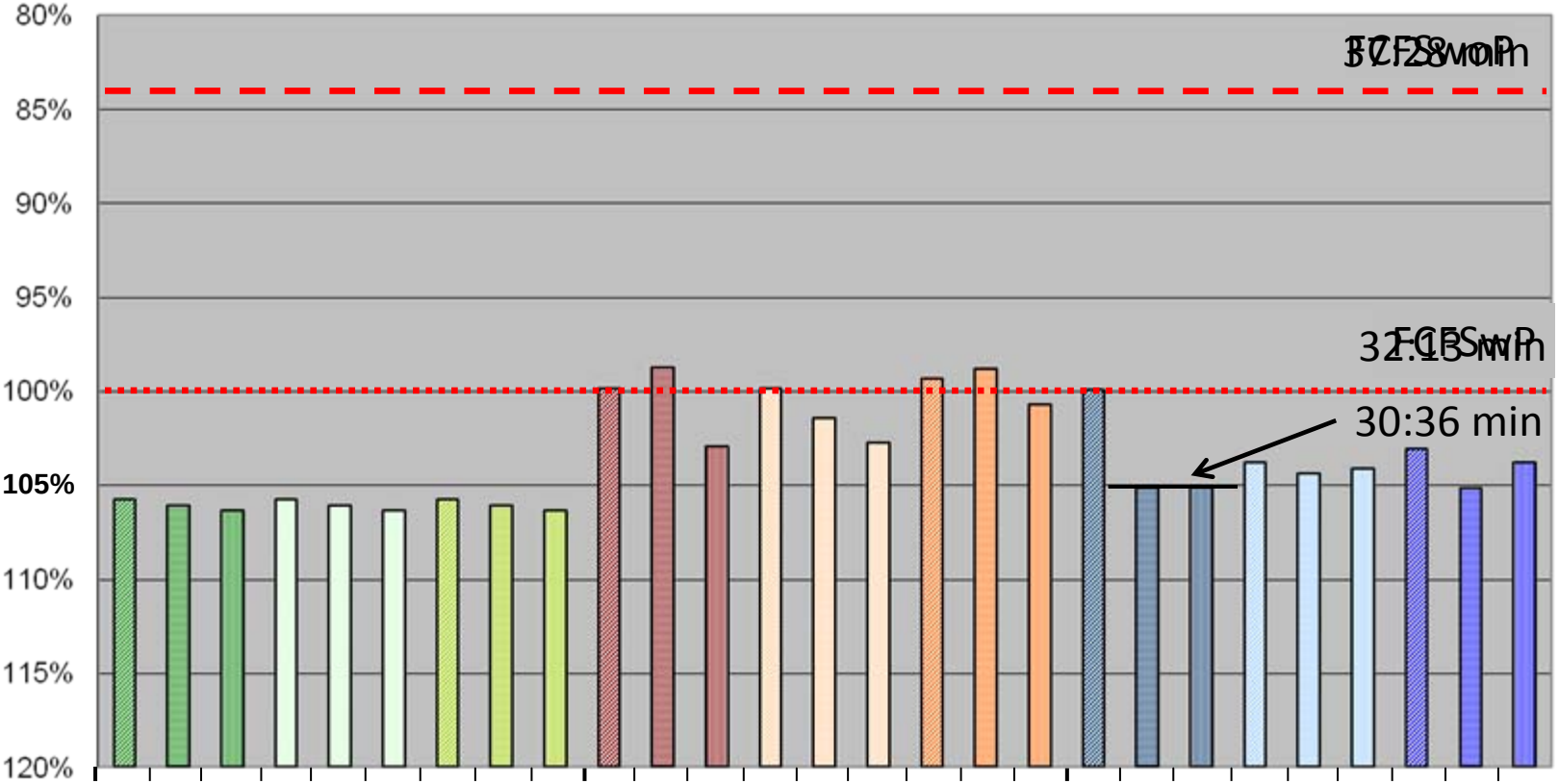
Approach:

- One randomly generated traffic sample
  - 20 aircraft / 30 min
  - 3 wake categories
  - 3 routes
  - 3 groups
- One run per scenario: 45 runs
- Constant ETA window for all aircraft in a run
- Constant pairing time window for all aircraft in a run

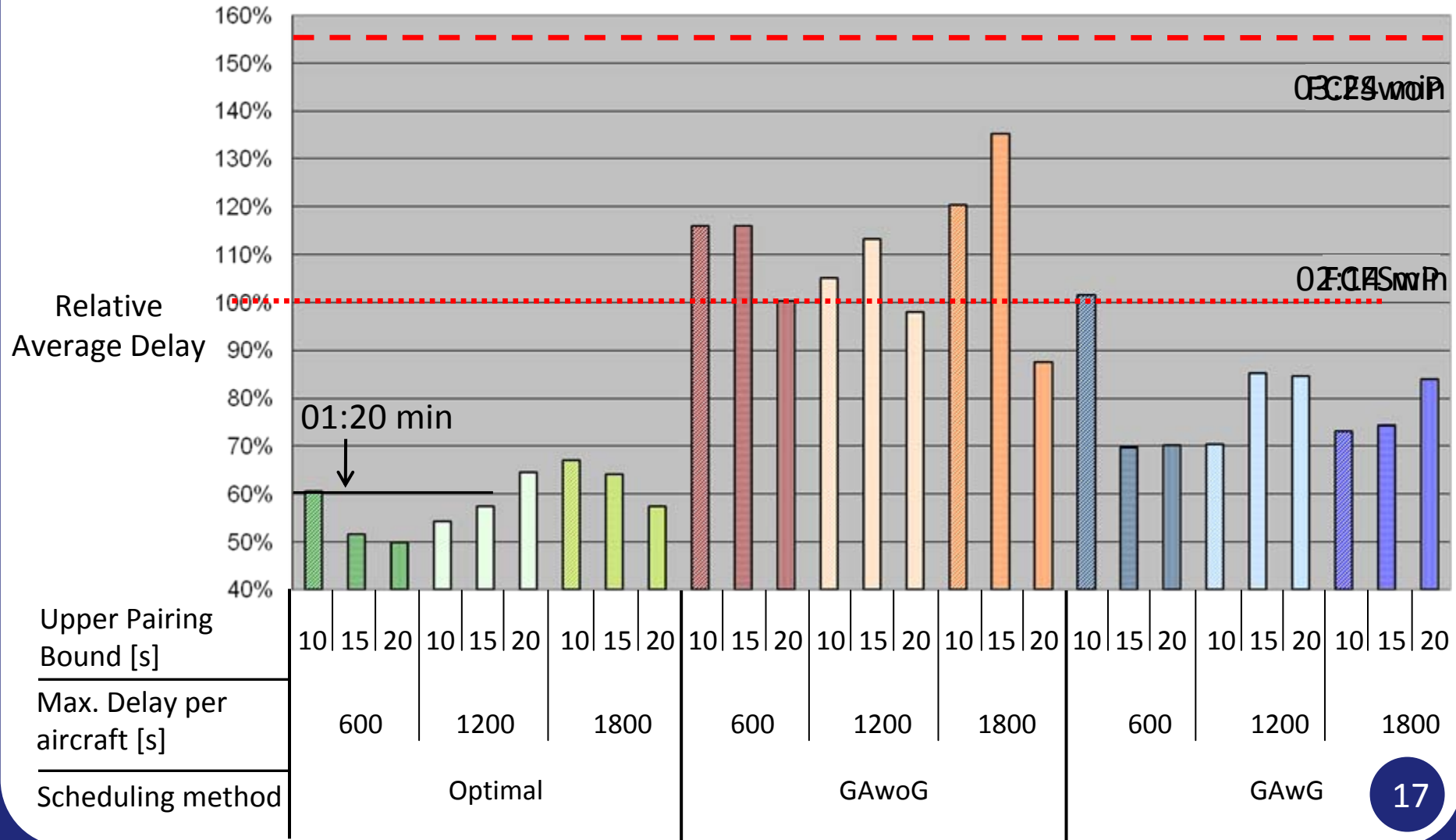
Assumptions:

- All aircraft have capabilities to perform very closely spaced parallel approaches:
  - Aircraft surveillance and aircraft-aircraft communication using ADS-B
  - High precision navigation systems (D-GPS)
  - Enhanced avionics (primary flight display, navigation display)
- 2 parallel runways
- Computation of earliest ETA and latest ETA: trajectory predictor available





Scheduling method	Optimal	GAwoG	GAwG


Relative Average Time Deviation from Earliest Possible ETA
Relative Average Delay
160%
150%
140%
130%
120%
110%
100%
90%
80%
70%
60%
50%
40%
01:20 min
Upper Pairing Bound [s]
10 15 20 10 15 20 10 15 20 10 15 20 10 15 20 10 15 20 10 15 20 10 15 20 10 15 20
Max. Delay per aircraft [s]
600 1200 1800 600 1200 1800 600 1200 1800
Scheduling method
Optimal
GAwoG
GAwG

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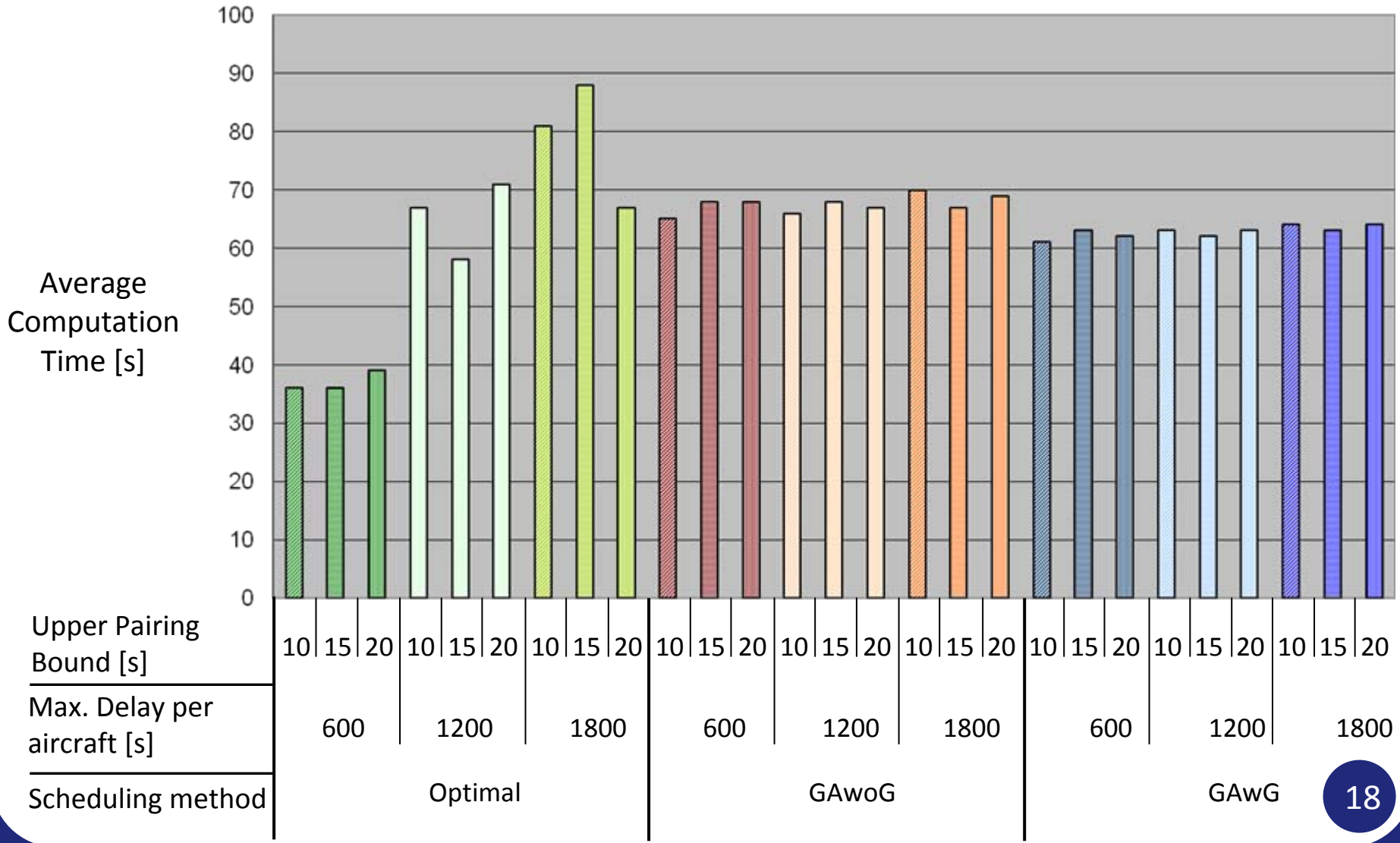
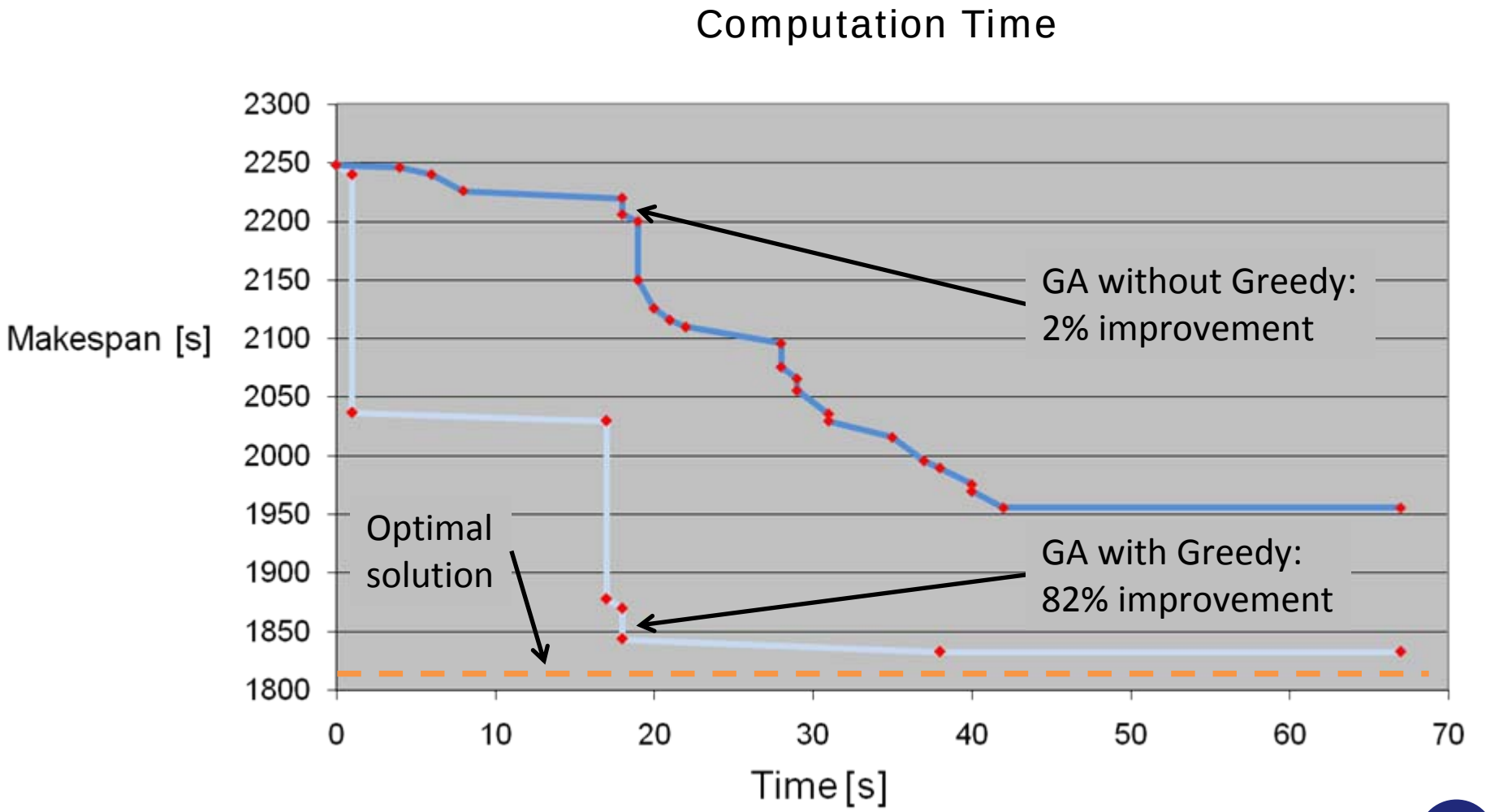
Average Computation Time




Computation Time
Makespan [s]
2300
2250
2200
2150
2100
2050
2000
1950
1900
1850
1800
0
10
20
30
40
50
60
70
Time [s]
GA without Greedy:
2% improvement
Optimal
solution
GA with Greedy:
82% improvement

Concluding remarks:

- Advanced scheduling methods improve throughput 5-6%
- Genetic Algorithm with Greedy shows better makespan and delay than FCFS with pairing
- Optimal solutions: computation times sensitive to changes of independent variables
- For simulations consider genetic algorithm with greedy improvement heuristic
- Future research:
  - More runs
  - Other optimization objectives
  - Other optimization methods
  - Robust schedules

Thank you for your Attention!

Decision variables:

$$z_{ij} \begin{cases} 1 & \text{if i and j are paired, and i is leading j} \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ij} \begin{cases} 1 & \text{if i and j are } \underline{\text{not}} \text{ paired, and i is leading j} \\ 0 & \text{otherwise} \end{cases}$$

Constraints:

- **Temporal constraint**: STA needs to be within earliest and latest ETA

$$t_i \in [t_{i,E-ETA}, t_{i,L-ETA}] \quad \forall i \in (1,\ldots,N)$$

- **Pairing constraint**: Two aircraft per pair

$$\sum_{j}^{N} z_{ij} \leq 1 \quad z_{ij} \in \{0,1\} \quad \forall i \in (1,\ldots,N)$$

$$\sum_{i}^{N} z_{ij} \leq 1 \quad z_{ij} \in \{0,1\} \quad \forall j \in (1,\ldots,N).$$

- **Sequencing constraint**: Paired or not paired

$$z_{ij} + z_{ji} + y_{ij} + y_{ji} = 1 \quad z_{ij}, z_{ji}, y_{ij}, y_{ji} \in \{0,1\}$$

$$\forall i, j \in (1,\ldots,N) \quad i \neq j$$

Constraints:

- **Separation constraint**:

  Standard separation between not paired aircraft.

$$t_j - t_i \geq -(y_{ji} + z_{ji}) \cdot M + y_{ij} \cdot sep_{ij}$$
$$y_{ji}, z_{ji}, y_{ij} \in \{0,1\} \quad \forall i, j \in (1,\ldots,N) \quad i \neq j$$

  Follower in a pair must be between some lower pairing bound (LPB) and upper pairing bound (UPB) behind its lead.

$$t_j - t_i \geq -(y_{ji} + z_{ji}) \cdot M + (y_{ij} + z_{ij}) \cdot LPB$$
$$z_{ji}, y_{ji} \in \{0,1\}$$

$$t_j - t_i \leq (y_{ij} + z_{ji}) \cdot M + z_{ij} \cdot UPB$$
$$z_{ji}, y_{ij} \in \{0,1\}$$

- **Route constraint**:

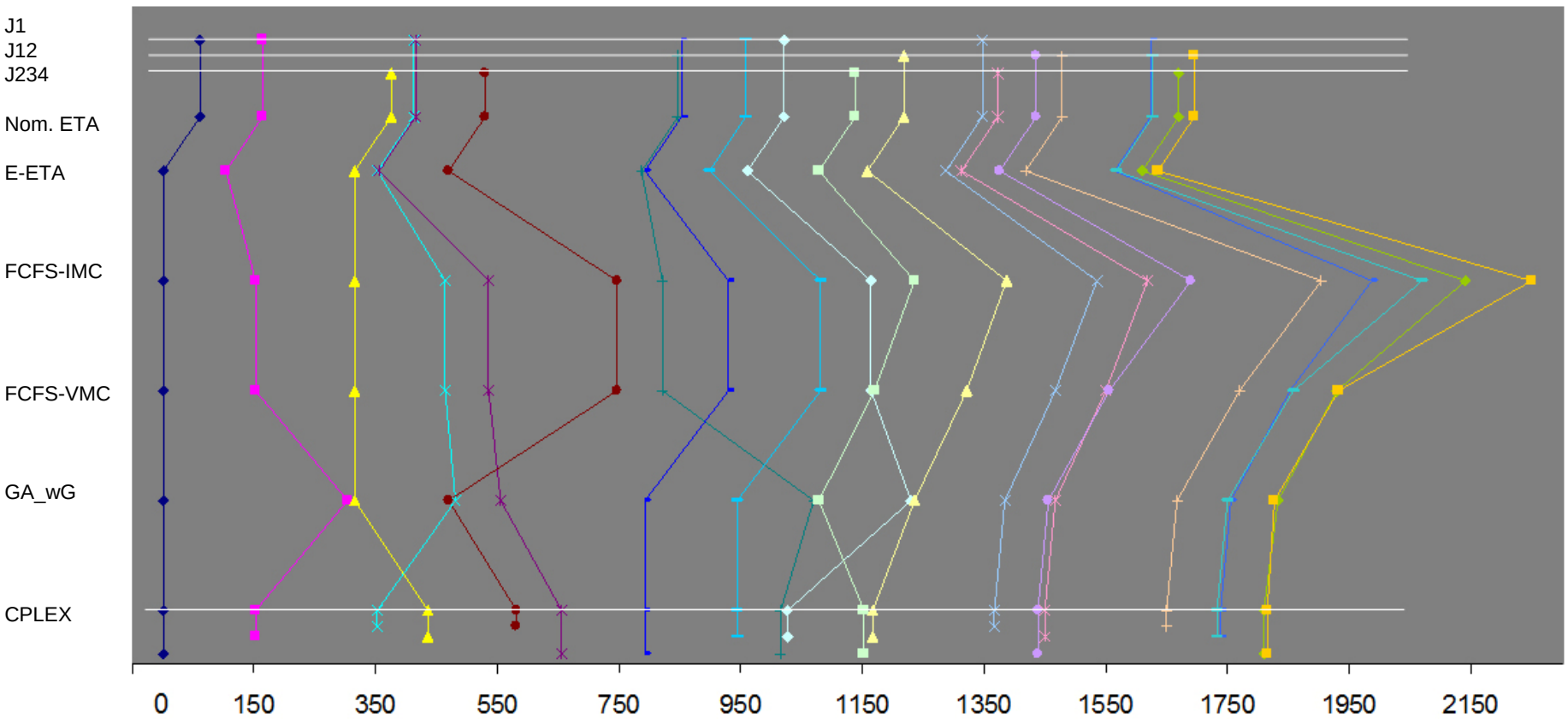
  If not paired and in trail on same route: no overtaking

$$t_j - t_i \geq -(y_{ij} + z_{ji}) \cdot M$$
$$\forall i, j \in (1,\ldots,N) \; i \neq j \quad if \quad r_i = r_j$$
$$and\ if \quad t_{i,ETA} < t_{j,ETA}$$

Constraints:

- **VCSPA grouping constraint**: paired aircraft must have similar performance (same VCSPA group)

$$z_{ij} = 0 \quad z_{ji} = 0 \quad if \quad g_i \neq g_j$$
$$\forall i, j \in (1,...,N) \quad i \neq j$$


Schedules for PTW: 5-15 sec, ETA time window: -60 - 1800
J1
J12
J234
Nom. ETA
E-ETA
FCFS-IMC
FCFS-VMC
GA_wG
CPLEX
0
150
350
550
750
950
1150
1350
1550
1750
1950
2150