Optimization of Airport Surface Traffic:

A Case-study of Incheon International Airport

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Contents

Introduction

- Incheon International Airport (ICN) in South Korea
  - Surface congestion due to continuously growing traffic demands
  - Airport expansion project in progress
  - Growing need for CDM and controller decision support tool

- Research Purpose
  - SW Development of a decision support tool for IADS (Integrated Arrival, Departure, Surface) operation in ICN
  - Research collaboration between Korea Aerospace Research Institute (KARI) and National Aeronautics and Space Administration (NASA)

- Operational characteristics analysis
- Simulation model development and validation

→ **Presented in ATIO 2016**

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- Surface/departure scheduler SW development
- Simulation-based test environment development

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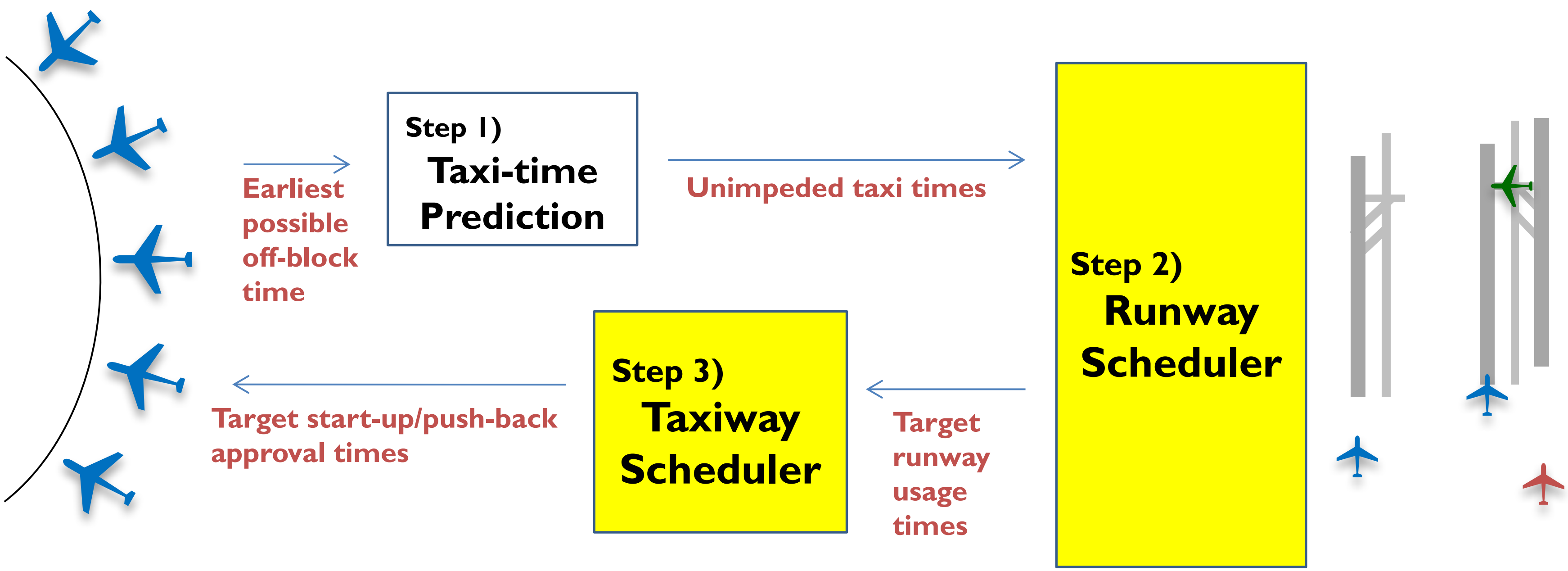
- Integrated test (including human-in-the-loop simulation)

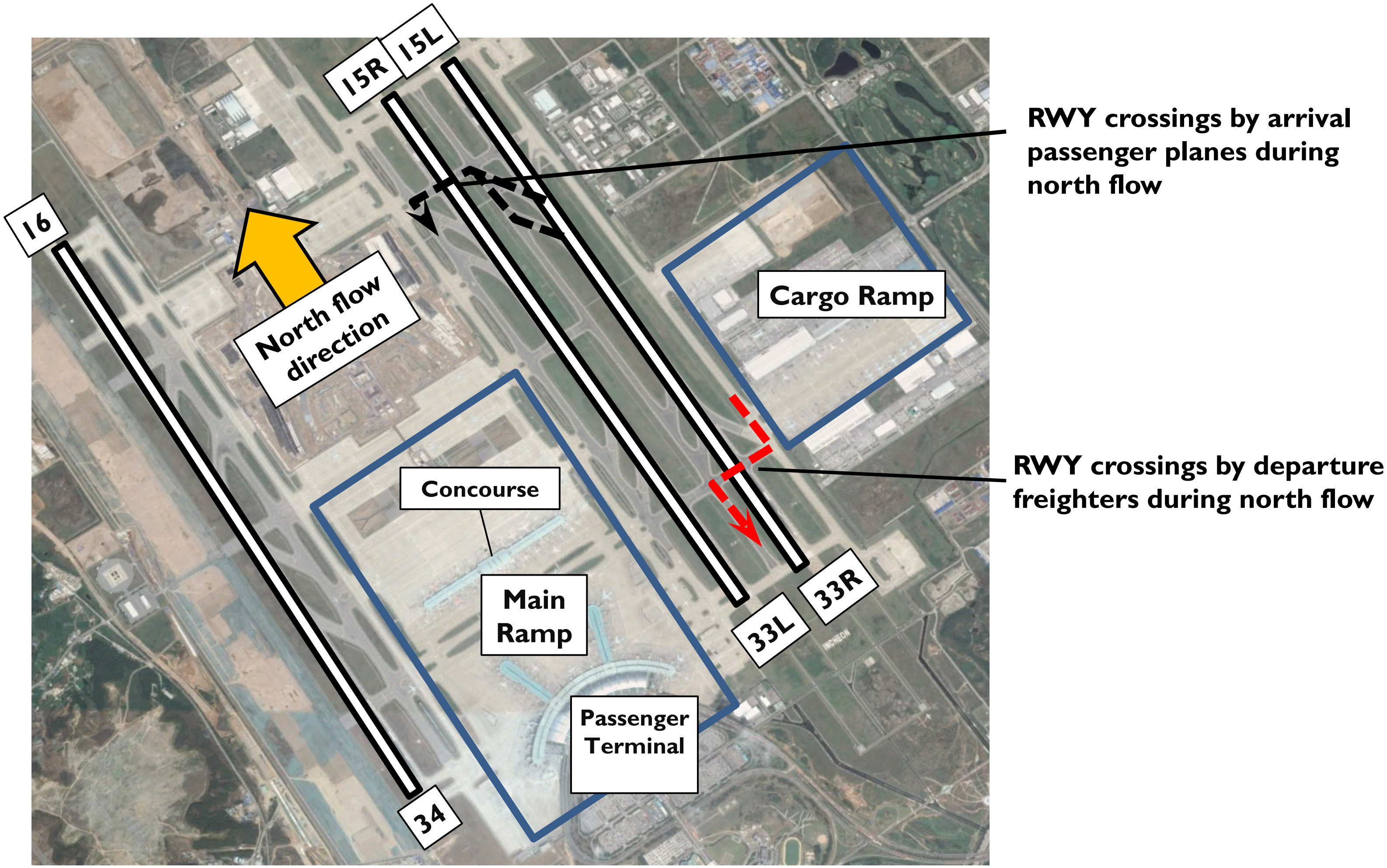
Introduction

- Research Direction
  - Based on 3-step approach



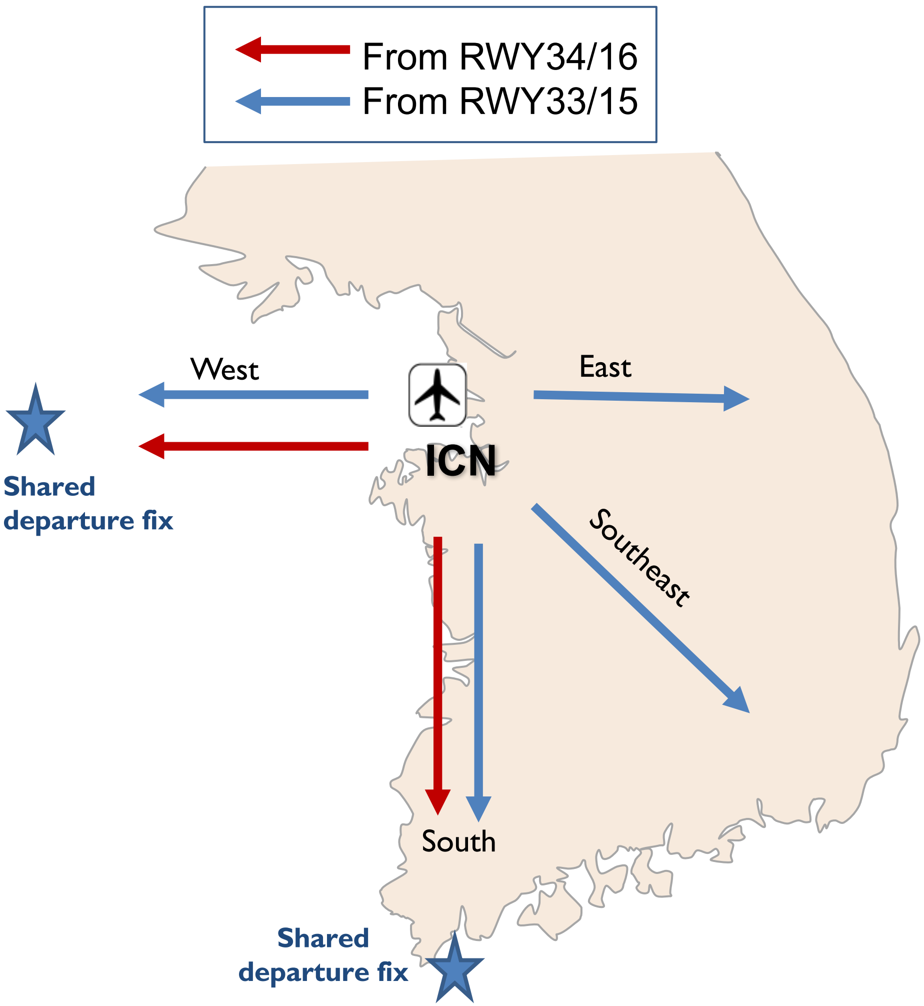
  - MILP-based optimization models were developed and tested.

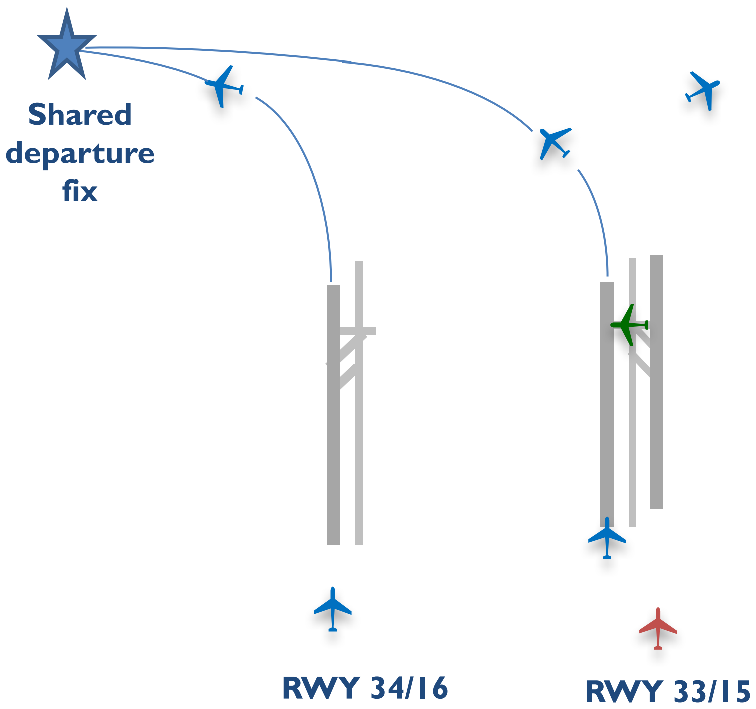
Scheduling Requirements



Airport Configuration

Scheduling Requirements

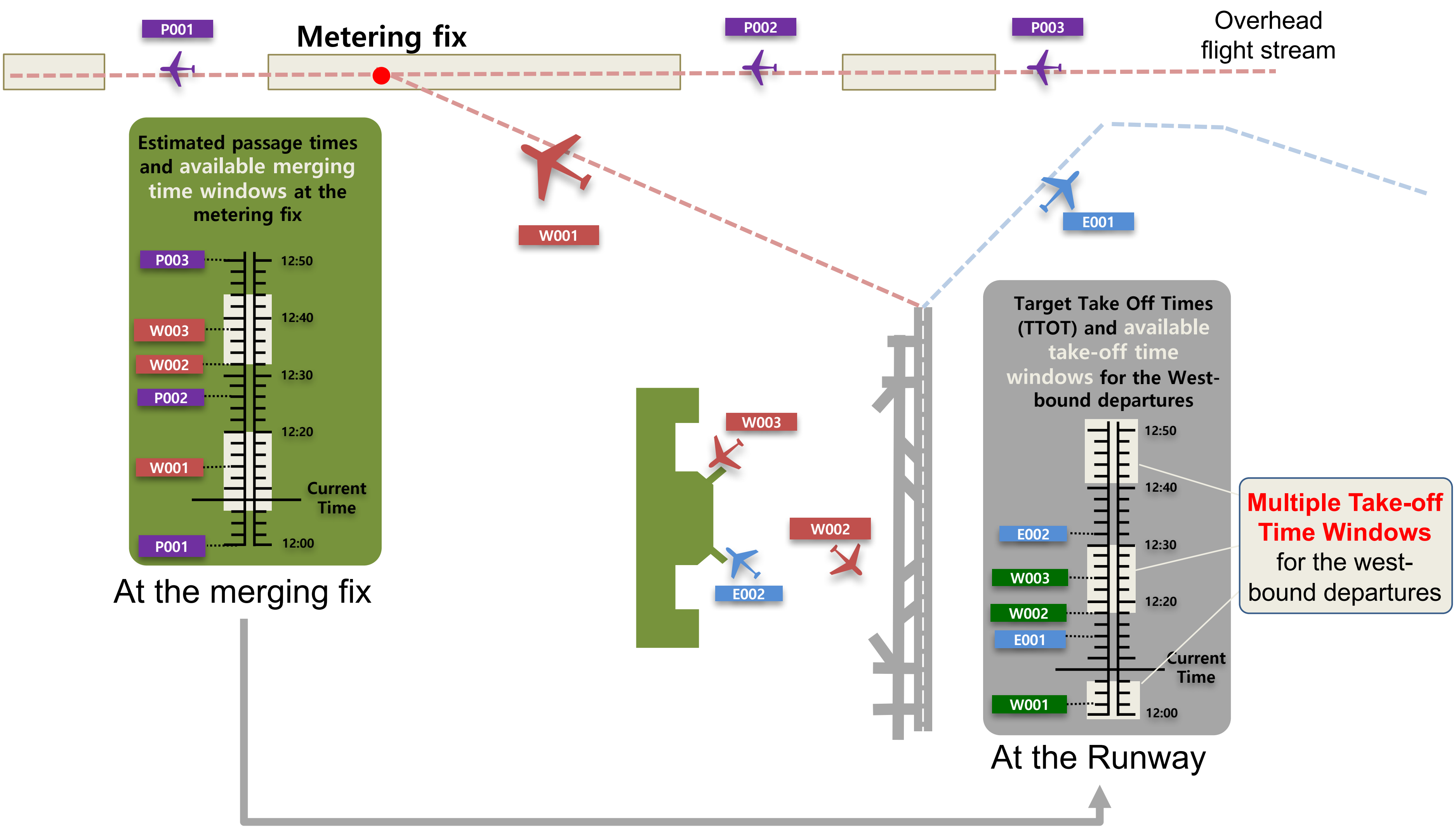




Departure route directions and a shared departure fix from the multiple runways in ICN

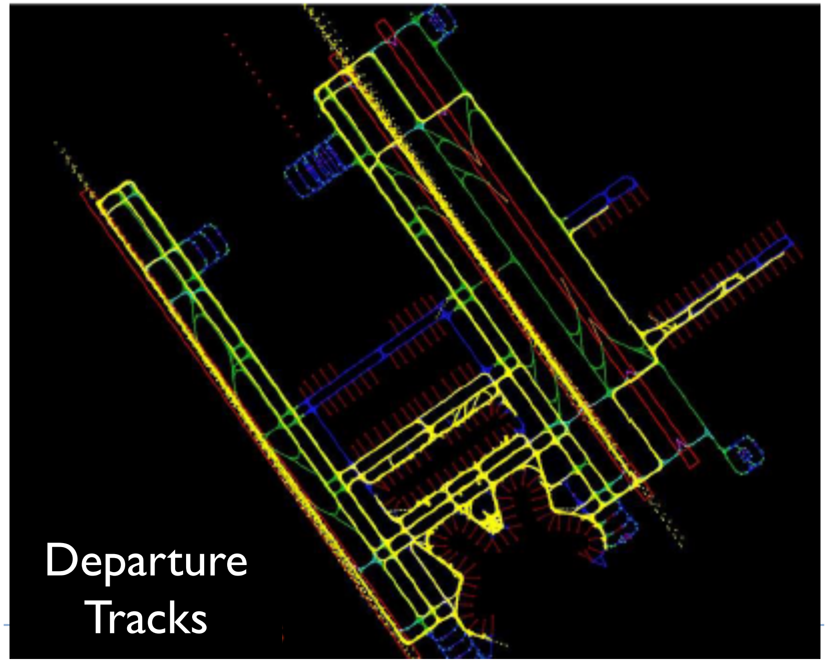
Scheduling Requirements

Multiple Take-off Time Windows



Scheduling Requirements

- Multiple runway scheduling
  - With shared departure fixes
- TMIs (Traffic Management Initiatives)
  - CFR
  - EDCT
  - MIT/MDI
  - Multiple takeoff time windows
- Runway crossings
  - Departure runway crossings by arrival flights
  - Arrival runway crossings by departure freighters
- Gate holding and pushback time limit
  - Earliest and/or latest takeoff time limit
- ELDT (Expected Landing Time)
  - Assumed to be given and not adjustable
- Taxi route of each aircraft
  - Assumed to be given and not adjustable



Runway Scheduling

$$\text{minimize} \quad \sum_{i \in D} \left(t_i - \text{EarliestT}_i \right)$$

$$\text{subject to} \quad z_{ij} + z_{ji} = 1, \quad \forall i, j \in D \cup A \cup C, \ i \neq j$$

$$t_j - t_i - \text{Rsep}_{ij} \geq -M\left(1 - z_{ij}\right), \quad \forall i, j \in D \cup A \cup C, \ i \neq j$$

$$\text{EarliestT}_i \leq t_i \leq \text{LatestT}_i, \quad \forall i, j \in D \cup A \cup C, \quad i \neq j$$

$$z_{ij} \in \{0, \ 1\}, \quad \forall i, j \in D \cup A \cup C$$

$$z_{ij} = 1, \quad \forall i, j \in D_{Class_k}, \quad \text{EarliestT}_i < \text{EarliestT}_j, \quad i \neq j$$

For ICN RWY scheduler,

$$\forall i \in D, \quad \begin{cases} \text{EarliestT}_i = \text{EarliestOffT}_i \\ \text{LatestT}_i = \text{EarliestOffT}_i + \text{MaxRunwayDelayT}_i \end{cases}$$

$$\forall i \in A, \quad \text{EarliestT}_i = \text{LatestT}_i = \text{OnT}_i$$

$$\forall i \in C, \quad \begin{cases} \text{EarliestT}_i = \text{OnT}_i + \text{TransT}_i \\ \text{LatestT}_i = \min\left\{ \text{OnT}_j + \text{TransT}_j \,\middle|\, \forall j \in C : \text{OnT}_i < \text{OnT}_j \right\} \end{cases}$$

Runway Scheduling

<Additional Constraints for TMIs>

- **EDCT, CFR → Adjustment of EarliestT_i and LatestT_i**

- **MIT(Miles-In-Trail), MDI (Minimum Departure Interval)**

In case of MIT) $$t_j - t_i + \left(\text{TansT}_j^k - \text{TransT}_j^k - \frac{\text{MIT}_k}{\text{TransV}_i^k} \right) \geq -M\left(1 - z_{ij}\right), \quad \forall i, j \in D_{MIT_k}, \; i \neq j$$

In case of MDI) $$t_j - t_i + \left(\text{MDI}_k\right) \geq -M\left(1 - z_{ij}\right), \quad \forall i, j \in D_{MDI_k}, \; i \neq j$$

- **Multiple Take-off Time Windows**

$$TimeW_i = \left\{ \left[\text{MinTime}_{i,1}, \text{MaxTime}_{i,1}\right], \left[\text{MinTime}_{i,2}, \text{MaxTime}_{i,2}\right], \cdots, \left[\text{MinTime}_{i,N_{W_i}}, \text{MaxTime}_{i,N_{W_i}}\right] \right\}$$

$$s_i^k = \begin{cases} 1 & \text{if} \quad \text{MinTime}_{i,k} \leq t_i \leq \text{MaxTime}_{i,k} \\ 0 & \text{otherwise} \end{cases}$$

$$s_i^k \in \{1,0\}, \quad \forall i \in D_{TimeW}, \; k \in (1..N_{W_i}), \qquad \sum_{k=1}^{N_{W_i}} s_i^k = 1, \quad \forall i \in D_{TimeW}$$

Taxiway Scheduling

$$\text{minimize } \alpha_p \left(\sum_{i \in D, r \in R} \max\left[t_{i,r} - \text{DesiredOffT}_{i,r},\ 0\right] \right)$$

Late Take-off Time

$$+ \alpha_d \left(\sum_{i \in D, r \in R} t_{i,r} - \sum_{i \in D, g \in G} t_{i,g} \right) + \alpha_a \left(\sum_{i \in A, g \in G} t_{i,g} - \sum_{i \in A, r \in R} t_{i,r} \right)$$

Departure Taxi-out Time **Arrival Taxi-in Time**

subject to

$z_{ij}^u \in \{0,\ 1\},\quad \forall i, j \in D \cup A,\ i \neq j,\ u \in I$ **Passage sequence of flight i and j at node u**

$t_{i,u} \geq 0,\quad \forall i \in D \cup A,\ u \in N$ **Passage time of flight i at node u**

$z_{ij}^u + z_{ji}^u = 1,\quad \forall i,j \in D \cup A,\ i \neq j,\ u \in I$ **Passage sequence at node u**

$t_{i,v} \geq t_{i,u} + \text{MinTaxiT}_{uv},\quad \forall i \in D \cup A,\ (u,v) \in E$ **Minimum travel time in link u-v**

$z_{ij}^u = z_{ij}^v,\quad \forall i,j \in D \cup A,\ i \neq j,\ u,v \in I,\ (u,v) \in E$ **No overtaking allowed along taxiways**

$z_{ij}^u + z_{ji}^v = 1,\quad \forall i,j \in D \cup A,\ i \neq j,\ u,v \in I,\ (u,v) \in E$ **Conflict free in bi-directional link**

Taxiway Scheduling

subject to (continued)

$$t_{j,u} - t_{i,u} - (t_{i,v} - t_{i,u})\frac{\mathrm{Dsep}_{ij}}{l_{uv}} \geq -(1 - z_{ij}^{u})M, \quad \forall i, j \in D \bigcup A, \; i \neq j, \; u \in I, \; (u,v) \in E$$

$$t_{j,v} - t_{i,v} - (t_{j,v} - t_{j,u})\frac{\mathrm{Dsep}_{ij}}{l_{uv}} \geq -(1 - z_{ij}^{v})M, \quad \forall i, j \in D \bigcup A, \; i \neq j, \; v \in I, \; (u,v) \in E$$

Maintaining required separations at intersections

$$t_{j,r} - t_{i,r} - \mathrm{Rsep}_{ij} \geq -(1 - z_{ij}^{r})M, \quad \forall i, j \in D, \; i \neq j, \; r \in R$$ **Runway separation**

$$t_{i,r} \geq \mathrm{EarliestOffT}_{i,r}, \quad \forall i \in D, \; r \in R$$ **Earliest take-off time**

$$t_{i,g} \geq \mathrm{OutT}_{i,g}, \quad \forall i \in D, \; g \in G$$ **Pushback ready time**

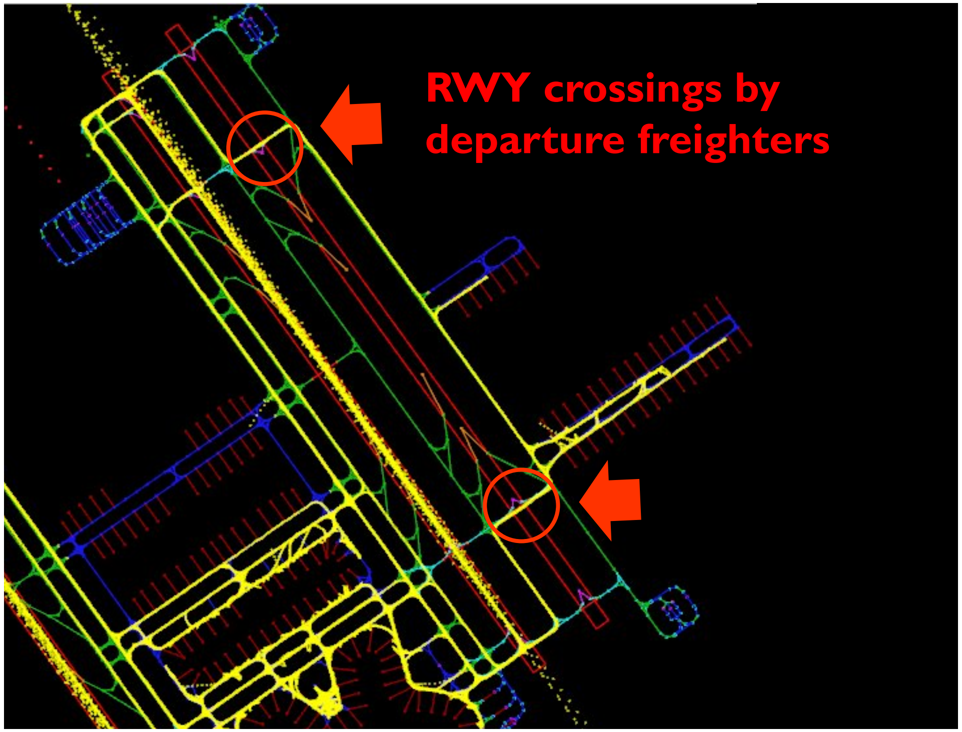
$$t_{i,g} \leq \mathrm{OutT}_{i,g} + \mathrm{MaxGateHold}_{i,g}, \quad \forall i \in D, \; g \in G$$ **Maximum gate holding time**

$$t_{i,r} = \mathrm{OnT}_{i,r}, \quad \forall i \in A, \; r \in R$$ **Arrival landing time**

$$t_{i,u} = \mathrm{FrozenT}_{i,u}, \quad \forall i \in D' \bigcup A', \; u \in N$$ **Frozen schedule**

Taxiway Scheduling

<Additional Constraints for RWY crossings >



Departure Tracks

C_{dep} : Set of departure freighters (which need to cross the arrival runway.)

$$C_{dep} \subset D$$

crossing sequence = departure sequence

$$z_{ij}^{c} = z_{ij}^{r} \quad \forall i, j \in C_{dep}, \; i \neq j, \quad r \in R$$

Runway separation with Arrivals

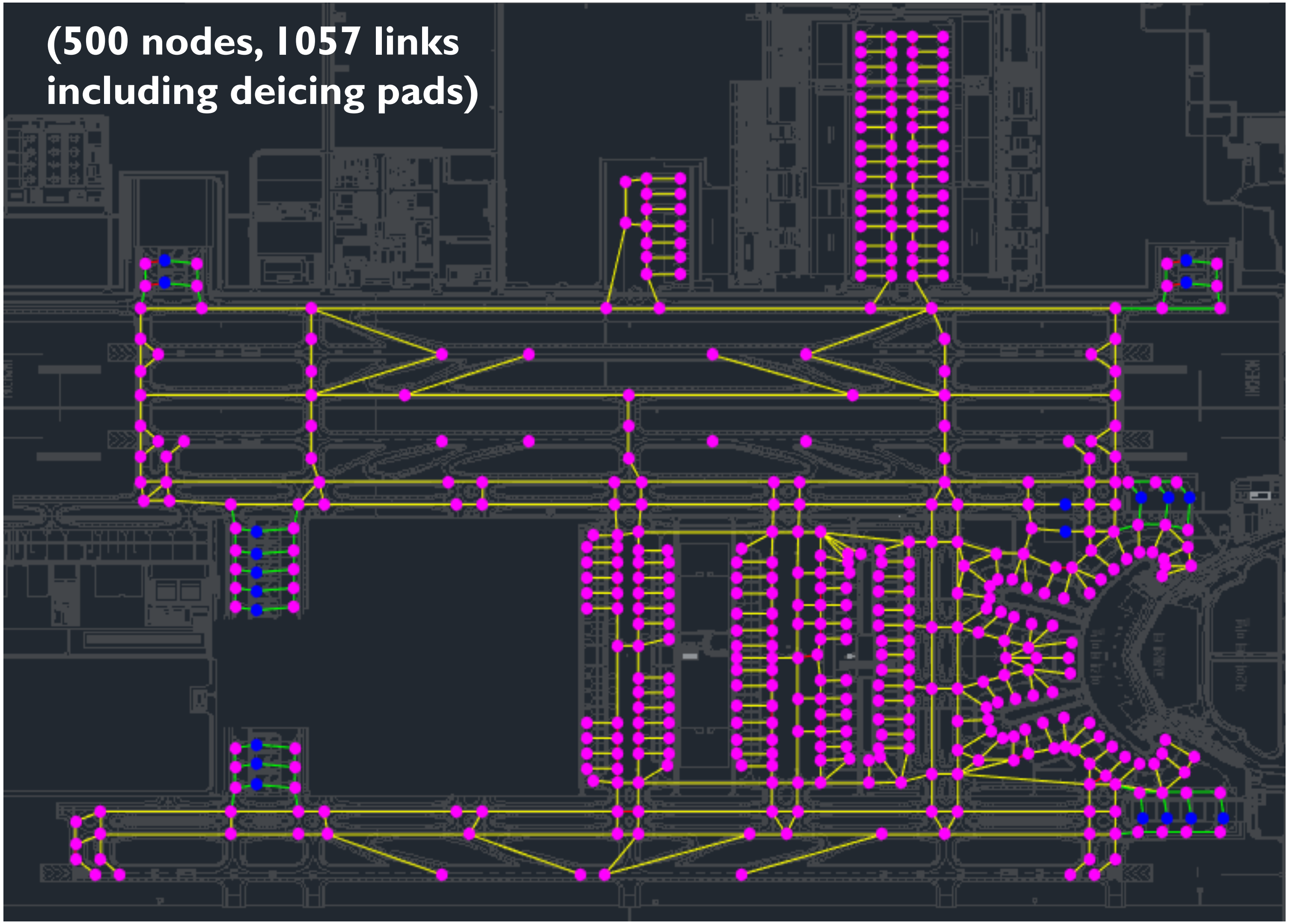
$$t_{j,r} - t_{i,c} - \mathrm{Rsep}_{ij} \geq -M\left(1 - z_{ij}^{crs}\right)$$

$$t_{i,c} - t_{j,r} - \mathrm{Rsep}_{ji} \geq -M \cdot z_{ij}^{crs}$$

$$z_{ij}^{crs} \in \{0,1\}, \quad \forall (i, j) \in \left(C_{dep} \times A\right)$$

Taxiway Scheduling

ICN Node-link model for taxiway scheduling



Optimization Tests

RWY separation matrix

Separation between Dep and Dep (sec)

		Tailing Aircraft			
		L	M	H	S
Leading aircraft	L	120	120	120	120
	M	180	120	120	120
	H	180	180	120	120
	S	180	180	120	120

Dep	L	M	H	S
	80	52	45	45

Arr	L	M	H	S
	85	47	40	40

Crs	L	M	H	S
	30	30	30	30

RWY occupancy times (sec)

Separation between Dep and Arr : RWY occupancy time of a preceding aircraft + 10sec
Separation between Dep and Crs : RWY occupancy time of a preceding aircraft + 10sec

Separation between operations on independent RWYs : 0sec

Optimization Tests

- Single Scenario Test
  - Purpose) Optimization results check for both runway scheduling and taxiway scheduling.
  - Test Scenario) Based on the real operation data of April 2015, the number of departures was assumed to be increased by 30% from a normal traffic volume.

- Monte-Carlo Test
  - Purpose) Computation time performance check for the multiple runway scheduling problem.
  - Test Scenario) Number of departures and arrivals are assumed to be same with the current peak time operation. For each test case, 100 randomly generated scenarios were used.

Optimization Tests – single scenario test

Scenario)

48 departures + 12 arrivals during 09:00-10:00

- 19 departures + 12 arrivals + 9 crossings on RWY33/15
- 29 departures on RWY34/16
- 4 departures from RWY33/15 and 11 departures from RWY34/16 merge into same route (South-bound)

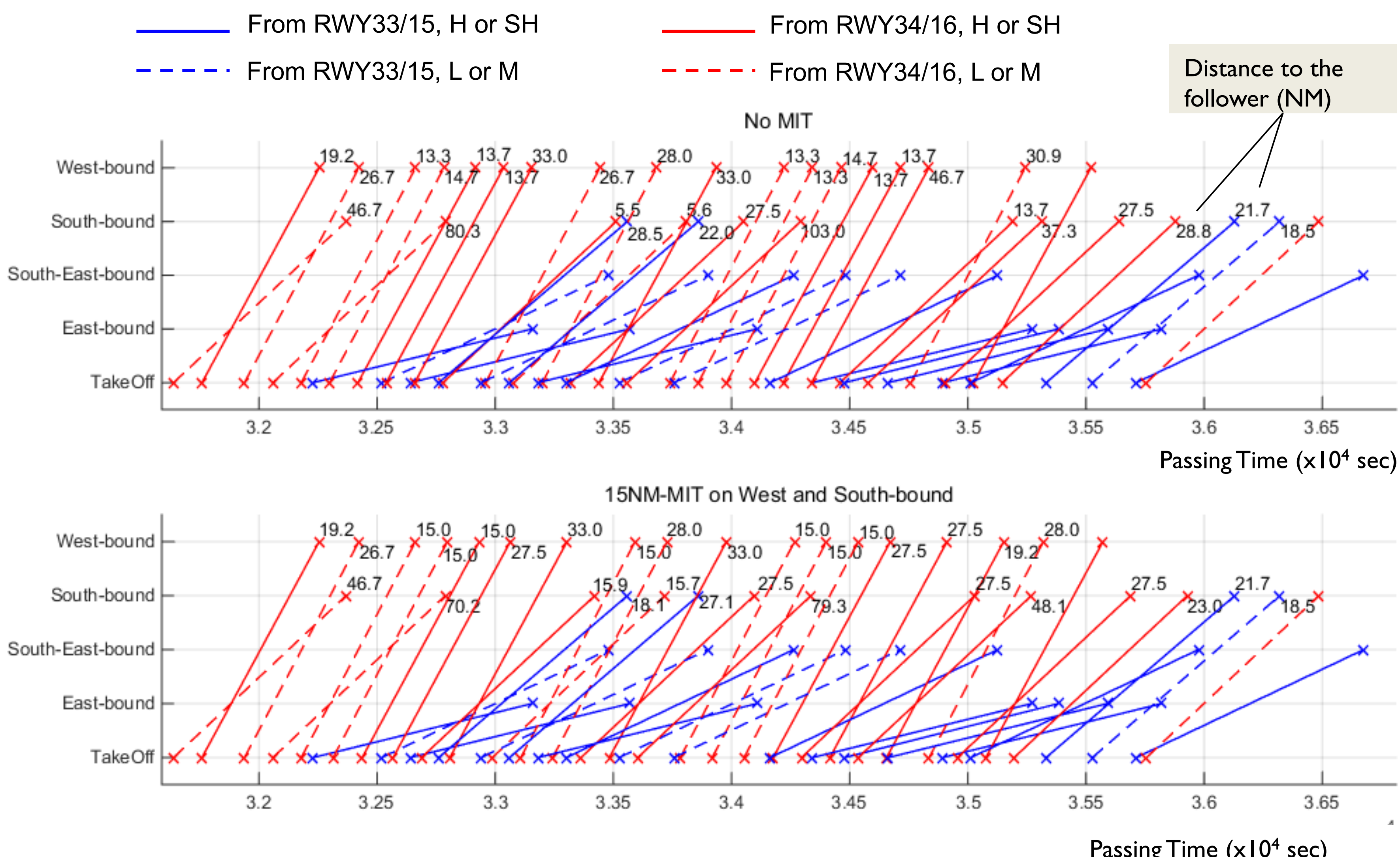
12 Arrivals	12 on RWY33/15	L	M	H	S	9 PAX(RWY crossing accompanied)+ 3 CGO			
			3	9					
48 Departures	19 on RWY33/15		5	13	1	W-bound	S-bound	SE-bound	E-bound
						0	4	8	7
	29 on RWY34/16		13	16		18	11	0	0

Constraints)

CPS : 3

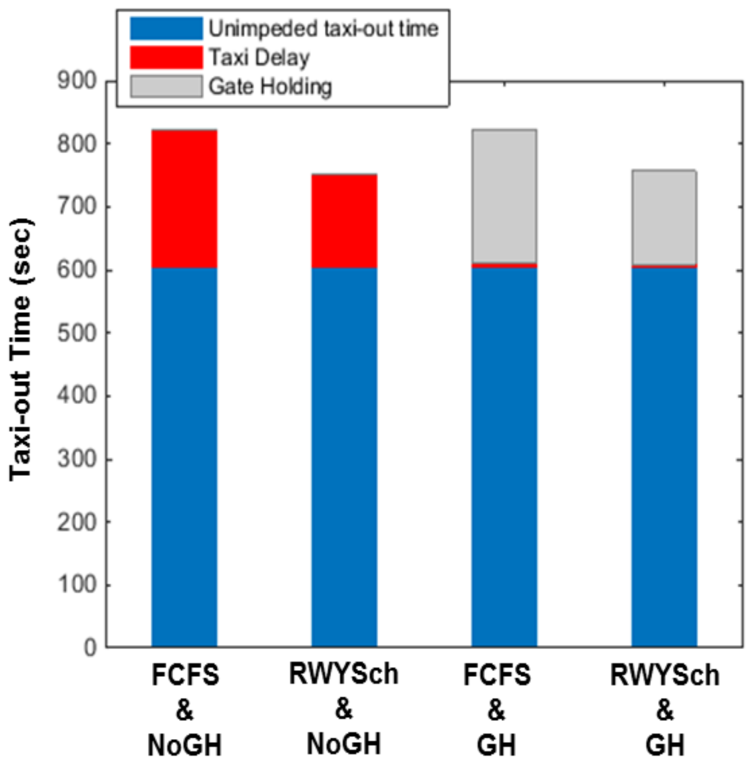
TMI : MIT on West-bound/South-bound

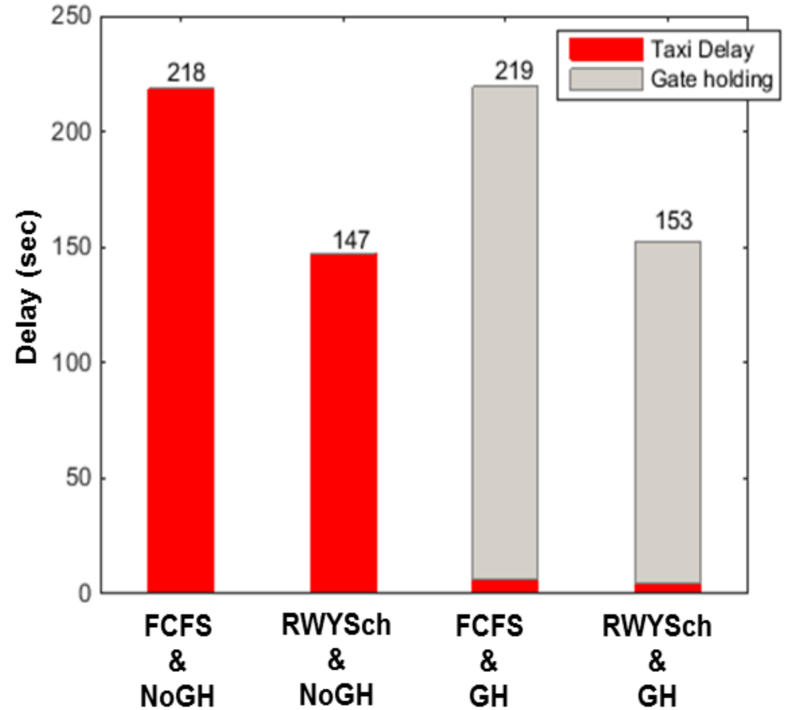
Optimization Tests – single scenario test



Passage Times and Separations at Departure Fixes

Optimization Tests – single scenario test



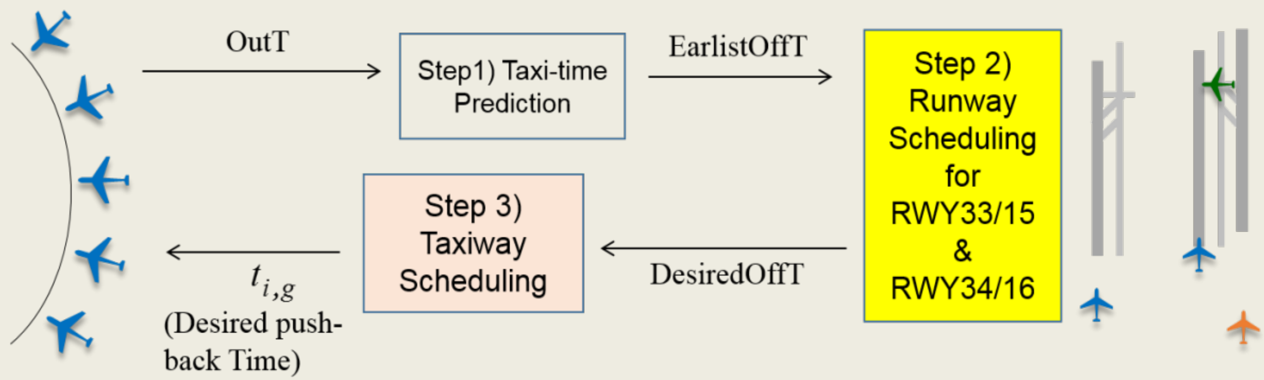


Averaged taxi-out time and delay per departure aircraft

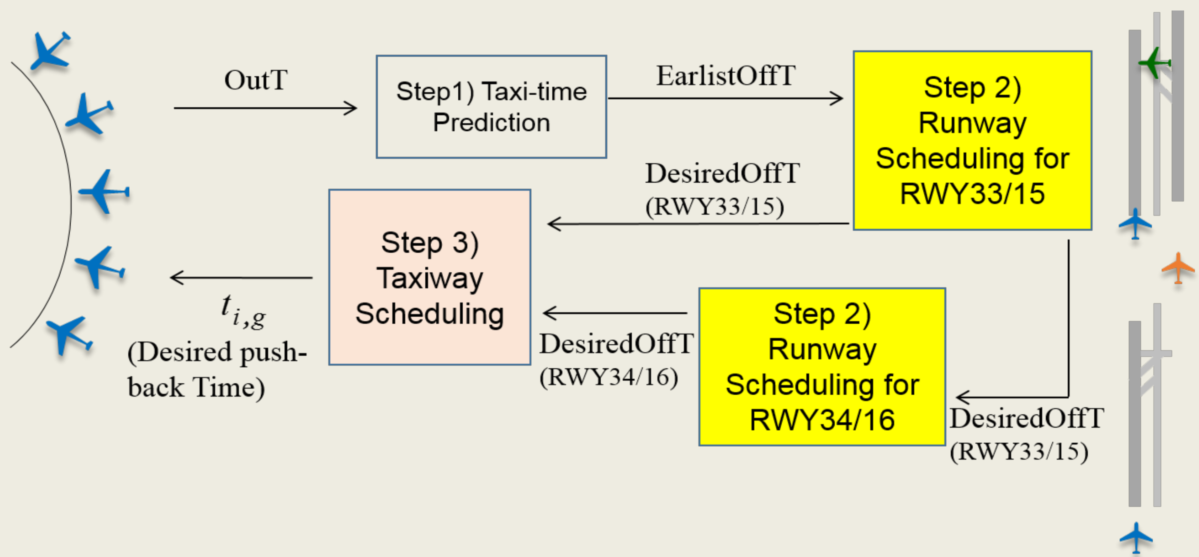
Optimization Tests – Monte-Carlo test

Two different methods for the multiple runway scheduling problem

Simultaneous optimization for the multiple runway scheduling



Sequential optimization for the multiple runway scheduling



Optimization Tests – Monte-Carlo test

Test scenarios

- 40 departures + 20 arrivals for 1 hour (the number of departure runways: 2)
- 15NM MIT separation on south-bound departures
  - Involves all south-bound departures from both runways to the shared departure fix.
- 100 random scenarios for each test case

	The total number of departures = 40	
	from RWY 33L/15R (to the shared fix)	from RWY 34/16 (to the shared fix)
Case 0	15 (5)	25 (10)
Case 1	14 (4)	26 (11)
Case 2	13 (3)	27 (12)
Case 3	12 (2)	28 (13)
Case 4	11 (1)	29 (14)
Case 5	10 (0)	30 (15)

- The total number of the south-bound departures to the shared departure fix are same.
- The south-bound departures which take-off from RWY 33L/15R were re-assigned to RWY34/16 one-by-one over case 0-5.

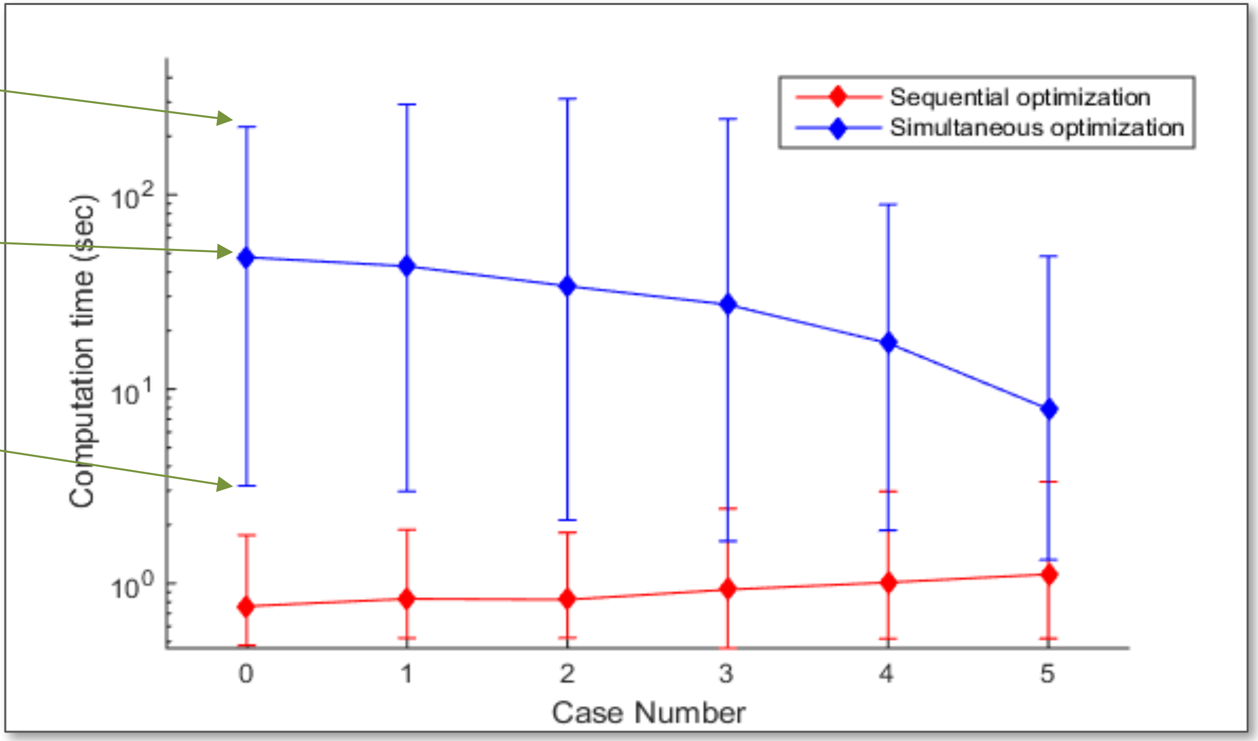
Optimization Tests – Monte-Carlo test

Test results: computation time comparison

90th percentile

Averaged computation time of 100 scenarios

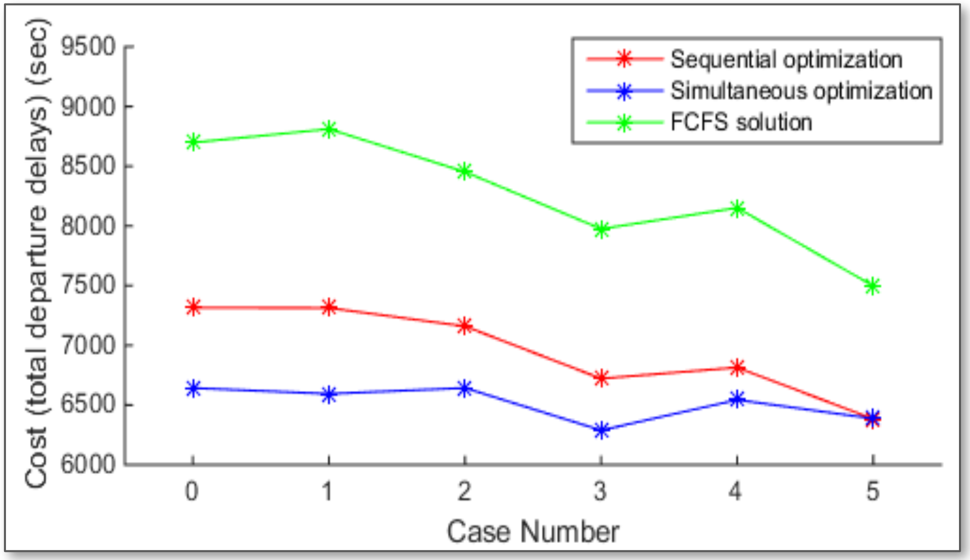
10th percentile



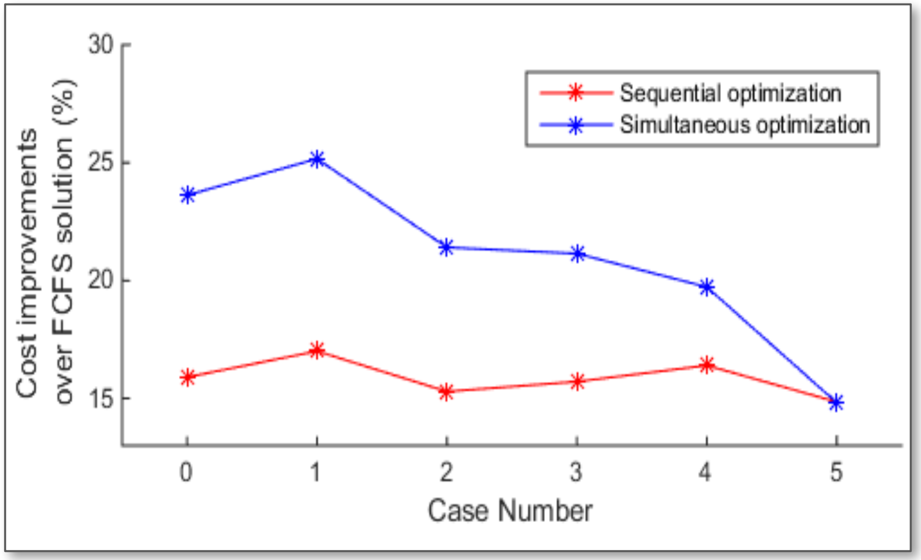
Computation time comparison in a log scale

Optimization Tests – Monte-Carlo test

Test results: Optimization cost comparison



Optimization cost comparison



Cost improvements over FCFS solution

Conclusion

- Developed the optimization models for airport surface traffic scheduling
  - MILP-based optimization models for runway scheduling and taxiway scheduling were developed and tested.
  - TMIs and operational characteristics which are specific to ICN were incorporated.
    - Multiple runway scheduling with consideration for MIT(Miles-In-Trail) separation at the shared departure fix
    - ‘Multiple take-off time windows’ constraints
    - Two different types of runway crossings on the coupled runways 33L/15R and 33R/15L.
- Suggested a method for better computation time performance
  - The sequential optimization using ‘multiple take-off time windows’ was proposed.
  - The sequential optimization shows much better performance with reasonably low cost for the multiple runway scheduling problem.

- Future Works
  - Integration of the additional requirements from ANSP (Air Navigation Service Provider) of ICN, such as cruise altitude assignment to the departure flights in pre-departure sequencing stage.
  - Runway assignment problem for runway balancing at an airport with multiple departure runways.

Thank You

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