A Tactical Scheduler for Surface Metering under Minimum Departure Interval Restrictions

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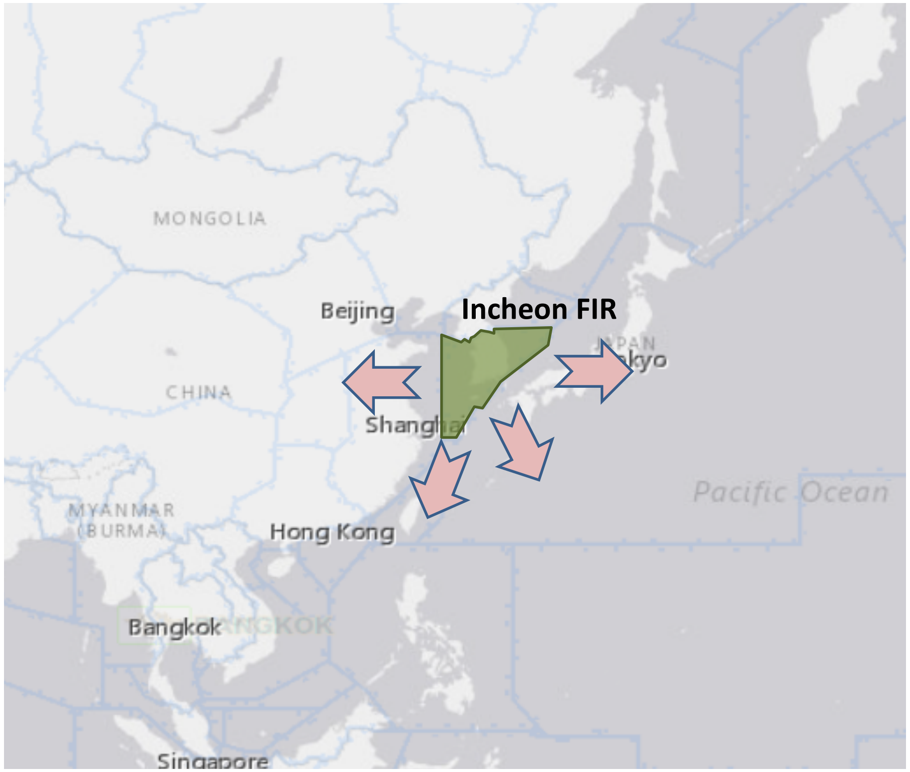
Outline

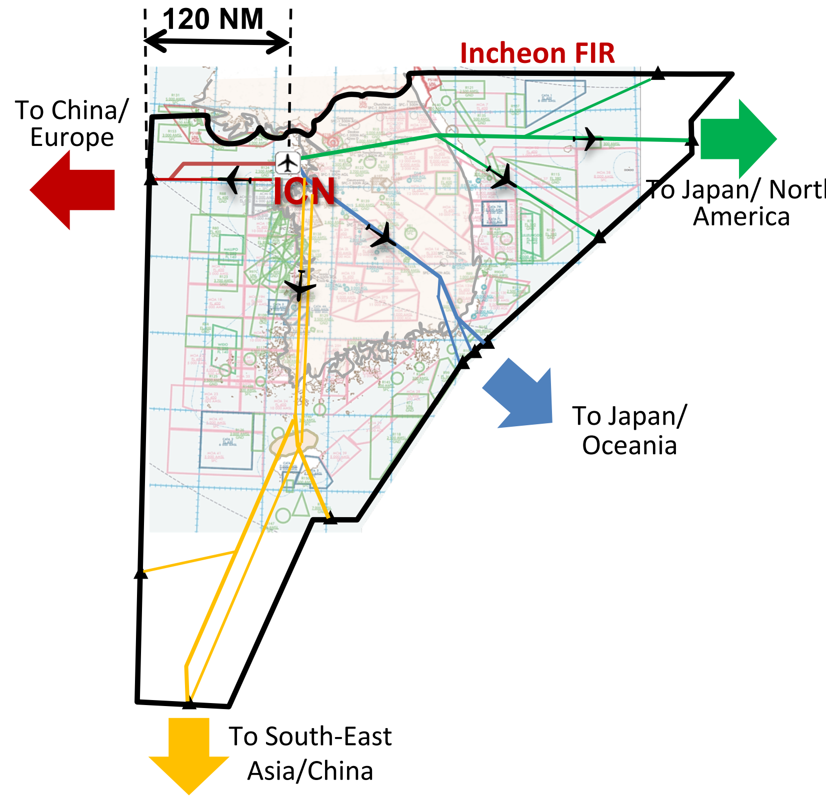
- **Motivation and Research Background**
- **MDI (Minimum Departure Interval) Restrictions** of Incheon International Airport in South Korea
- **Runway Scheduling** with MDI Restrictions
- Algorithm Evaluation based on **Fast-time Simulations**
- **Simulation Results**
- **Conclusions**

Motivation

- ATFM (Air Traffic Flow Management) TMIs (Traffic Management Initiatives)
  - **GDP (Ground Delay Program)** : assigns affected departures CTOTs (Calculated Take-Off Times).
  - **MDI (Minimum Departure Interval)**: time-based separation requirements between departures on the same SID (Standard Instrument Departure).
  - **MIT (Miles-in-Trail)** : distance-based separation requirements between aircraft flying through airspace resources (airport, fix, sector, route, etc.).
- MDIs of Incheon International Airport in South Korea
  - The time-based separation requirements between departures flying over a fix, through an airspace sector, on a route, flying to a destination area, or arriving at an airport.
  - Imposed on more than 90% of the departures.

ICN (Incheon International Airport)





- One of the hub airports in East Asia : 99% of the flights in 2018 were international.
- Surrounded by a lot of restricted areas and has short distance to the FIR boundaries.

MDI Restrictions of ICN

- Separation Requirement:

  Minimum 12min separation between aircraft exit Incheon FIR through FIR boundary fix MUGUS/ATOTI, entering Manila FIR using the route N892, and landing on the airport VV**, WM**, WS**
- Applied time: 2018.06.28 00:40~17:00 UTC
- Reason: bad weather

<MDI execution request in a plain text form>

	Conditions						Separation Requirement				Activation Schedule	
MDI Name	Destinations				FIR Exit Fix	Route	Default		For a Sub-group		StartTime (UTC)	EndTime (UTC)
	Flight A		Flight B									
	Area	Airport Code	Area	Airport Code			Type	Value (sec)	Pattern	Min. Time Span (sec)		
Additional _01		VV**/ WM**/ WS**		VV**/ WM**/ WS**	ATOTI/MUGUS	N892, KABAM	TIME	720			00:40	17:00

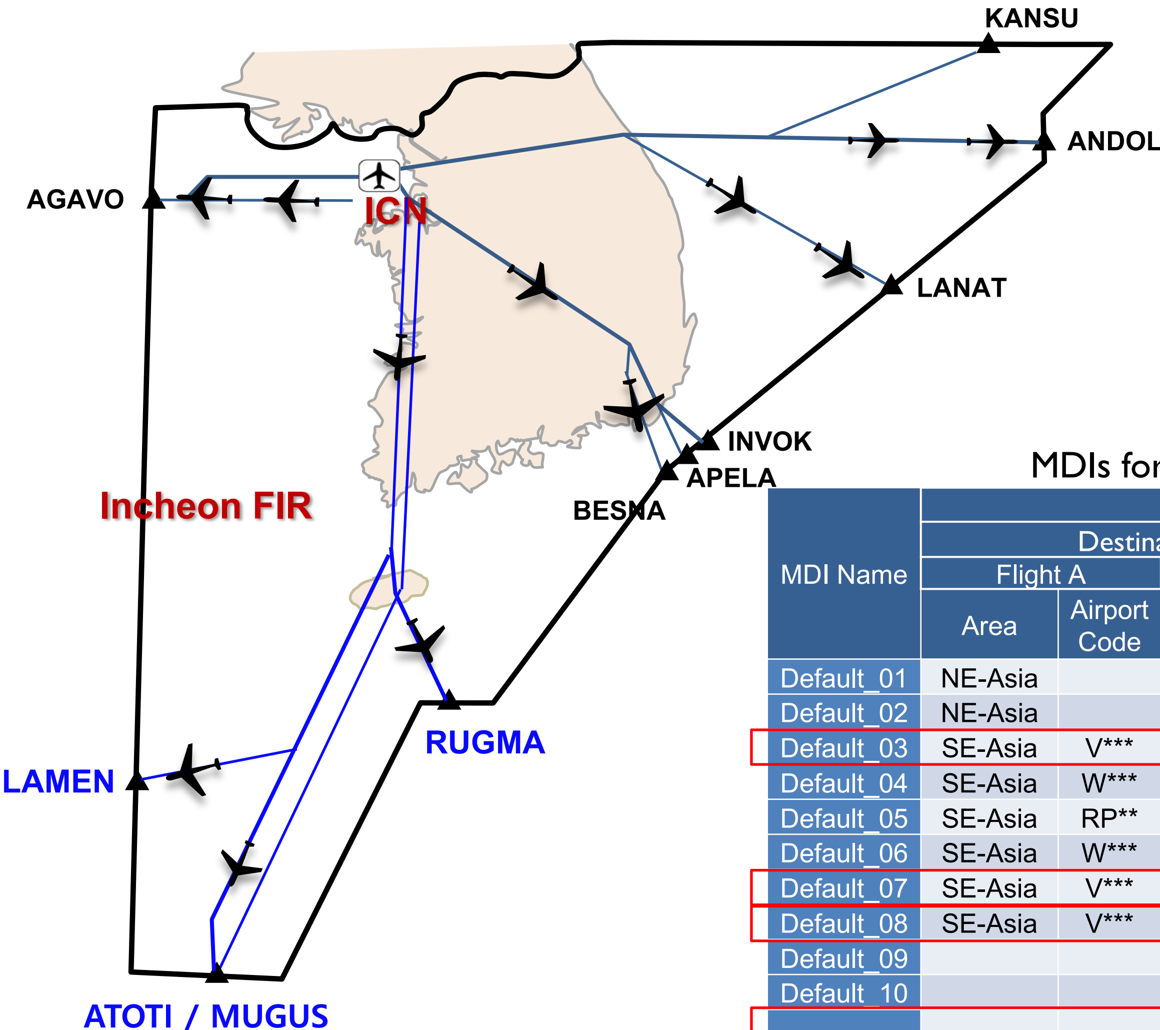
<MDI expression in a table form>

MDI Restrictions of ICN

MDI Name	Conditions						Separation Requirement				Activation Schedule	
	Destinations				FIR Exit Fix	Route	Default		Additional		StartTime (UTC)	EndTime (UTC)
	Flight A		Flight B									
	Area	Airport Code	Area	Airport Code			Type	Value (sec)	Pattern	Min. Time Span (sec)		
Default_01	NE-Asia		NE-Asia		ATOTI/MUGUS		TIME	180			0:00	24:00
Default_02	NE-Asia		SE-Asia		ATOTI/MUGUS		TIME	180			0:00	24:00
Default_03	SE-Asia	V***	SE-Asia	V***	ATOTI/MUGUS		TIME	360			0:00	24:00
Default_04	SE-Asia	W***	SE-Asia	W***	ATOTI/MUGUS		TIME	360			0:00	24:00
Default_05	SE-Asia	RP**	SE-Asia	RP**	ATOTI/MUGUS		TIME	360			0:00	24:00
Default_06	SE-Asia	W***	SE-Asia	RP**	ATOTI/MUGUS		TIME	360			0:00	24:00
Default_07	SE-Asia	V***	SE-Asia	W***	ATOTI/MUGUS		TIME	180			0:00	24:00
Default_08	SE-Asia	V***	SE-Asia	RP**	ATOTI/MUGUS		TIME	180			0:00	24:00
Default_09					RUGMA		TIME	180			0:00	24:00
Default_10					LAMEN		TIME	360			0:00	24:00
Default_11					ATOTI/MUGUS/LAMEN /RUGMA		WAKE_TIME	#			0:00	24:00
Default_12	Japan		Japan		LANAT/KANSU/ANDOL		TIME	180			0:00	24:00
Default_13	Japan		N. America		LANAT/KANSU/ANDOL		TIME	180			0:00	24:00
Default_14	N. America		N. America		LANAT/KANSU/ANDOL		TIME	180			0:00	24:00
Default_15	N. America		N. America		LANAT		TIME	360			23:00	11:00 (+1day)
Default_16	N. America		N. America		ANDOL		TIME	360			23:00	11:00 (+1day)
Default_17	N. America		N. America		KANSU		TIME	360			23:00	11:00 (+1day)
Default_18	N. America		N. America		LANAT		TIME	180	D-D-D-D	720	11:00	23:00
Default_19	N. America		N. America		ANDOL		TIME	180	D-D-D-D	720	11:00	23:00
Default_20	N. America		N. America		KANSU		TIME	180	D-D-D-D	720	11:00	23:00
Default_21	China		China		AGAVO		TIME	180			0:00	24:00
Default_22	China		Europe		AGAVO		TIME	180			0:00	24:00
Default_23	Europe		Europe		AGAVO		TIME	300			0:00	24:00
Default_24	Japan		Japan		APELA/BESNA		TIME	180			0:00	24:00
Default_25	Domestic		Domestic			A582	TIME	120			0:00	24:00
Default_26	Oceania		Oceania		APELA/BESNA		TIME	360			0:00	24:00

MDI Restrictions of ICN

Example of MDI restrictions imposed on the south-bound departures



"WAKE-TIME" separations (sec)

		Following aircraft			
		Light	Medium	Heavy	Super Heavy
Leading aircraft	Light	120	180	180	180
	Medium	120	120	180	180
	Heavy	120	120	120	180
	Super Heavy	120	120	120	120

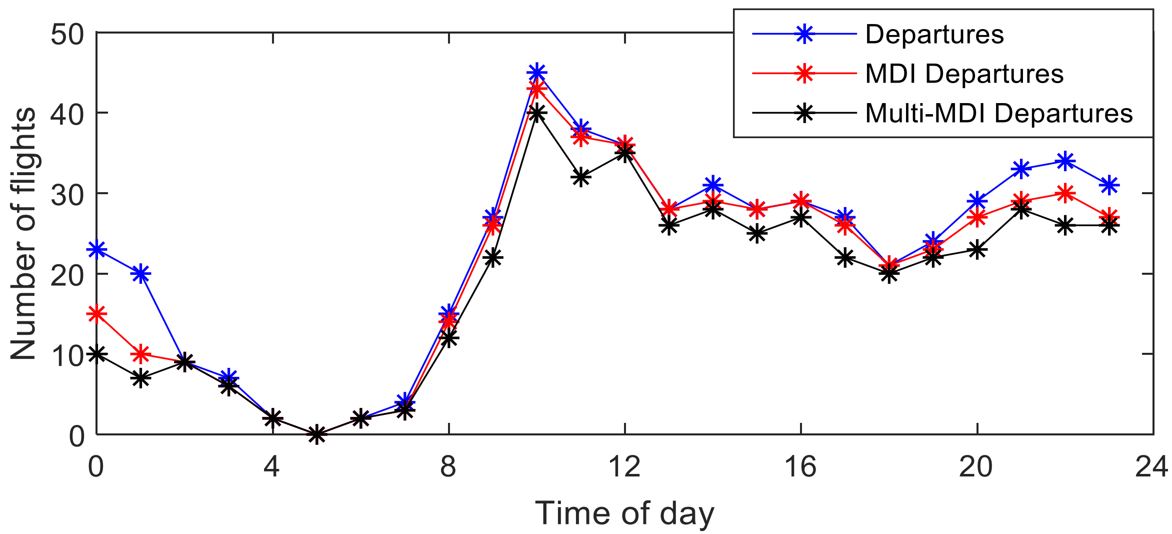
MDIs for South-bound Departures

MDI Name	Conditions					Separation	
	Destinations				FIR Exit Fix	Type	Value (sec)
	Flight A		Flight B				
	Area	Airport Code	Area	Airport Code			
Default_01	NE-Asia		NE-Asia		ATOTI/MUGUS	TIME	180
Default_02	NE-Asia		SE-Asia		ATOTI/MUGUS	TIME	180
Default_03	SE-Asia	V***	SE-Asia	V***	ATOTI/MUGUS	TIME	360
Default_04	SE-Asia	W***	SE-Asia	W***	ATOTI/MUGUS	TIME	360
Default_05	SE-Asia	RP**	SE-Asia	RP**	ATOTI/MUGUS	TIME	360
Default_06	SE-Asia	W***	SE-Asia	RP**	ATOTI/MUGUS	TIME	360
Default_07	SE-Asia	V***	SE-Asia	W***	ATOTI/MUGUS	TIME	180
Default_08	SE-Asia	V***	SE-Asia	RP**	ATOTI/MUGUS	TIME	180
Default_09					RUGMA	TIME	180
Default_10					LAMEN	TIME	360
Default_11					ATOTI/MUGUS/ LAMEN/RUGMA	WAKE_ TIME	#

MDI Restrictions of ICN

How many departures are subject to MDI restrictions?

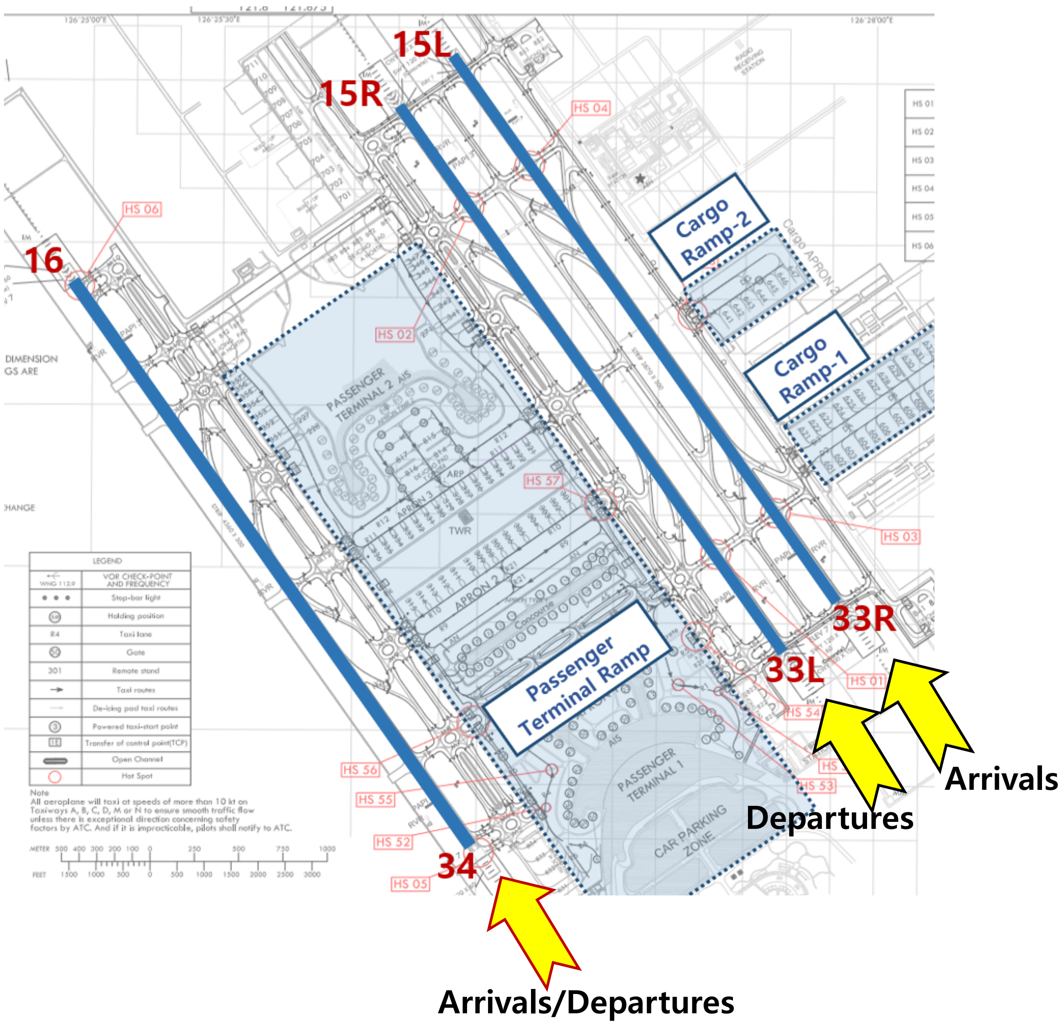
- On October 11, 2018 (a typical day having only the default MDIs)
  - 92% of departures had to comply with MDIs (= “MDI Departures”)
  - 90% of the MDI departures had to comply with multiple MDIs (= “Multi-MDI Departures”)



MDI Departure Rate Variation (October 11, 2018)

Runway Scheduling with MDI Restrictions

ICN airport configuration

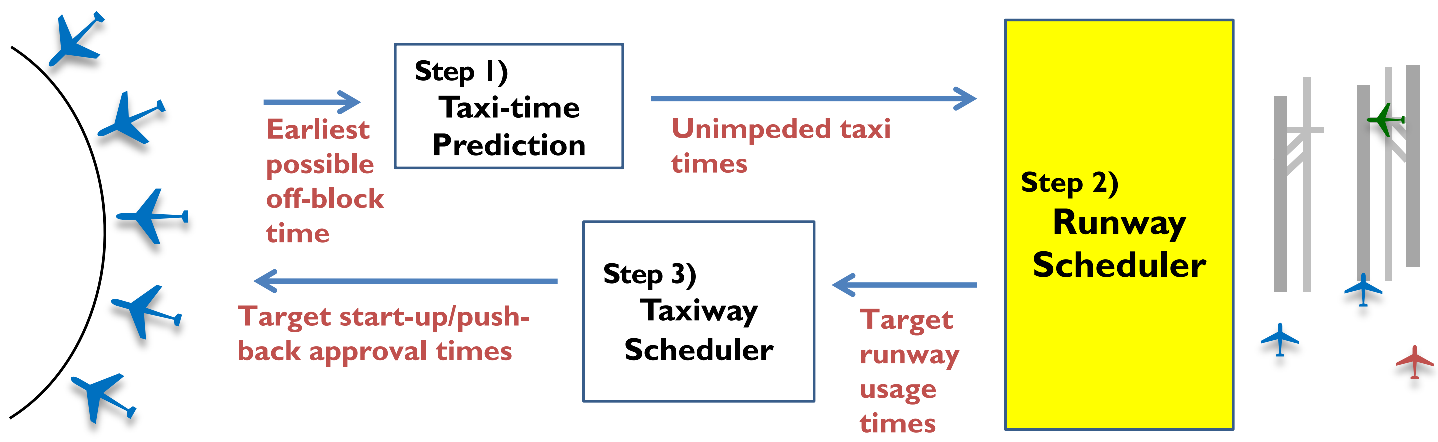


Key Requirements for scheduling

- Wake turbulence-based runway separation between take-offs should be complied with.
- The MDI restrictions should be complied with by the departure flights, regardless of their takeoff runways.
- Input for each departure flight
  - TOBT : Target Off-Block Times (= pushback ready time)
  - Assigned runway for takeoff
  - Unimpeded taxi-out time to the runway

Runway Scheduling with MDI Restrictions

Scheduling Algorithm Structure (3-step approach)



- In the previous study [1], MILP-based optimization models for runway scheduler and taxiway scheduler were developed and tested.
- **The purpose of this study is to develop the runway scheduler with the MDI restrictions for a practical implementation.**

[1] Y. Eun, et al., "Optimization of Airport Surface Traffic: A Case-study of Incheon International Airport," the 17th AIAA Aviation Technology, Integration, and Operations Conference, Denver, CO, June 2017.

Runway Scheduling with MDI Restrictions

Greedy style algorithm to determine the takeoff sequence

- **DEP**: a set of departure aircraft of which TTOTs need to be determined.
- **SCH**: a set of past runway usages including aircraft takeoffs and landings.
- **DEP_TTOT**: a set of departure aircraft having TTOTs assigned. Initially, an empty set.
- **AvailTime** : a set of time slots available for TTOT of a departure.
- **BlockTime**: a set of time slots not available (or blocked) for TTOT of a departure.

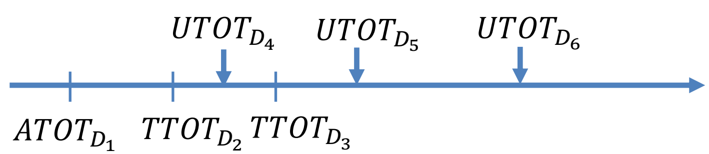
For example,

ATOT: Actual Take-Off Time
TTOT: Target Take-Off Time
UTOT: Unimpeded Take-Off Time

$\{D_1\} \subset \mathbf{SCH}$

$\{D_2, D_3\} \subset \mathbf{DEP\_TTOT}$

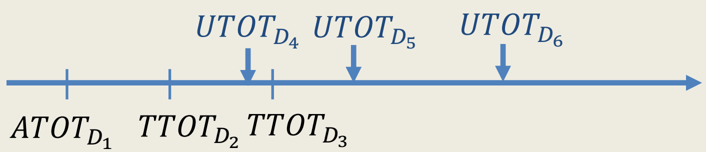
$\{D_4, D_5, D_6\} \subset \mathbf{DEP}$



→ Which aircraft would be the best to takeoff right after D_3 ?

Runway Scheduling with MDI Restrictions

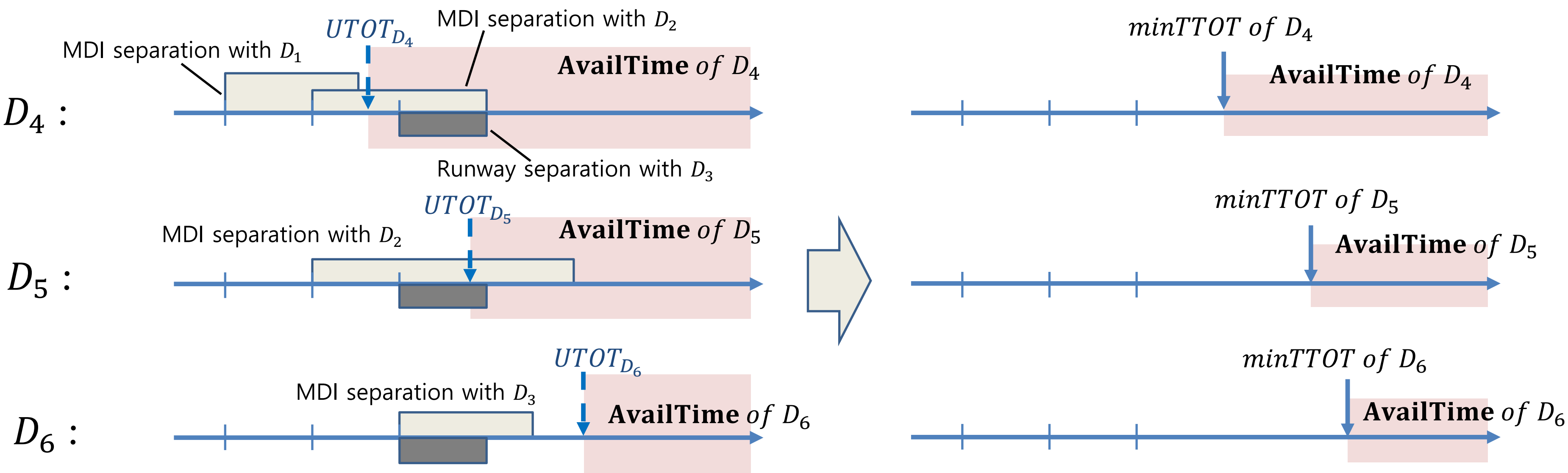
Greedy style algorithm to determine the takeoff sequence



D_4 has MDI separations with D_1 and D_2 .

D_5 has MDI separation with D_2 .

D_6 has MDI separation with D_3 .



D_4 should takeoff after D_3.

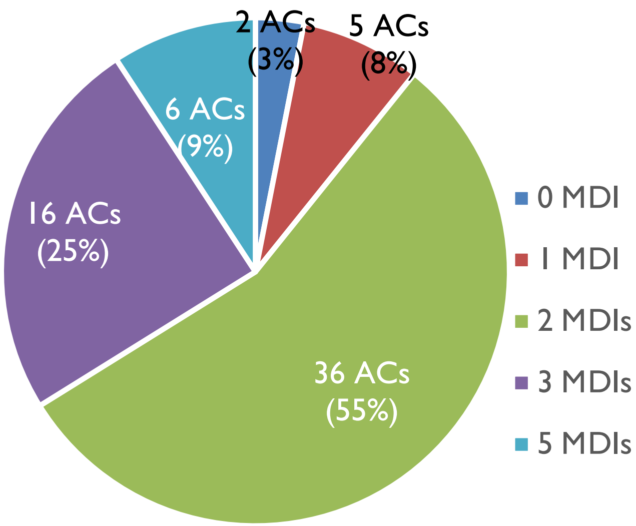
- Determine TTOT of D_4 as $minTTOT\ of\ D_4$ and put D_4 into **DEP_TTOT**.
- Repeat this until there are no departure flights remained in **DEP**.

Algorithm Evaluation based on Fast-time Simulation

Simulation Scenario Set-up

- Generated based on the real-operation data
  - 09:00 – 10:40 (KST, local time) on October 11, 2018
- Includes 17 arrivals (on RWY 33R)
- Includes 65 departures
  - Takeoffs from each runway: RWY 33L – 26 departures, RWY 34 – 39 departures
  - 63 MDI-compliant departures out of total 65 departures

<Number of flights subject to the MDI Constraints>

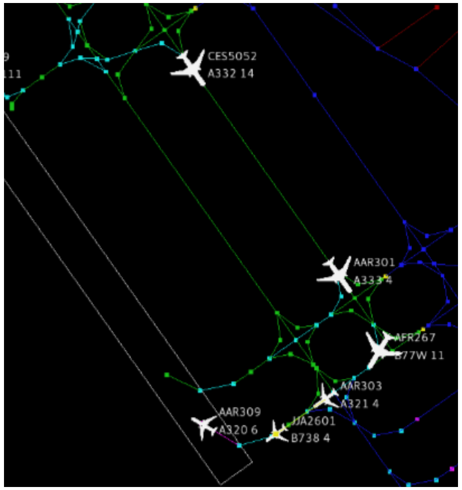


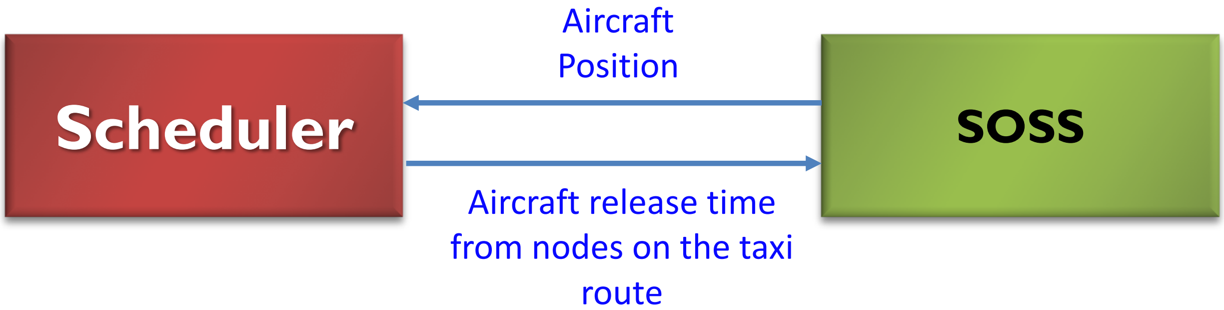
Algorithm Evaluation based on Fast-time Simulation

Software Set-ups for Fast-time Simulation

- Fast-time Simulation Tool : NASA's SOSS (Surface Operations Simulator and Scheduler)

    - SOSS is capable of controlling aircraft surface movement by releasing the aircraft from the node at a given time from an external scheduling module.





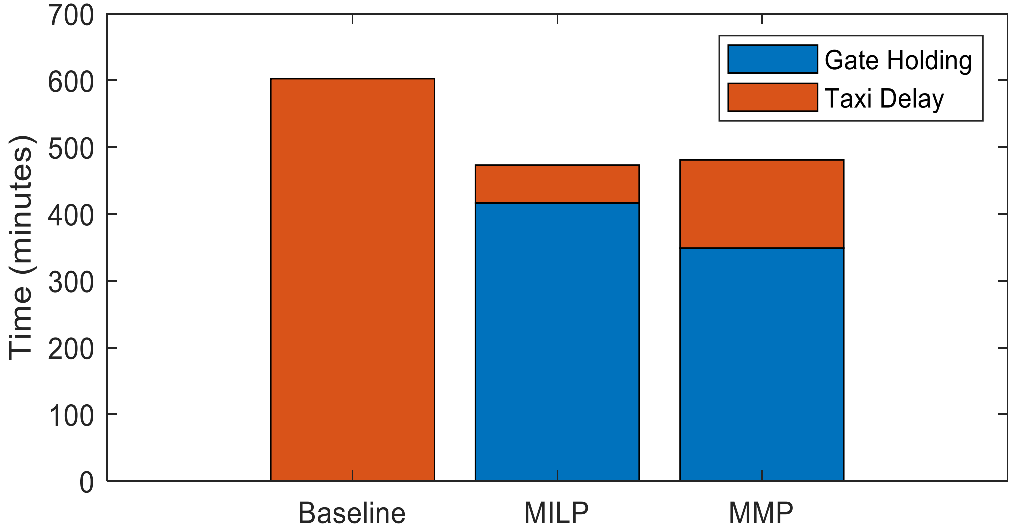
Algorithm Evaluation based on Fast-Time Simulation

What we are comparing for the results

	Scheduler	Stands for
Baseline	Not used	Current day operation
MILP	Used (TSATs from the scheduler are the optimization results of MILP-based models for runway and taxiway scheduling.)	Optimized schedule for minimizing the total taxi delay times (as strategic pre-departure scheduling)
MMP	**Used**	**A tactical scheduler**

* MMP : MIDAS** Main Processor (The prototype of surface metering tool developed for ICN)
** MIDAS : Management on Integrated operations of Departure, Arrival, and Surface Traffic

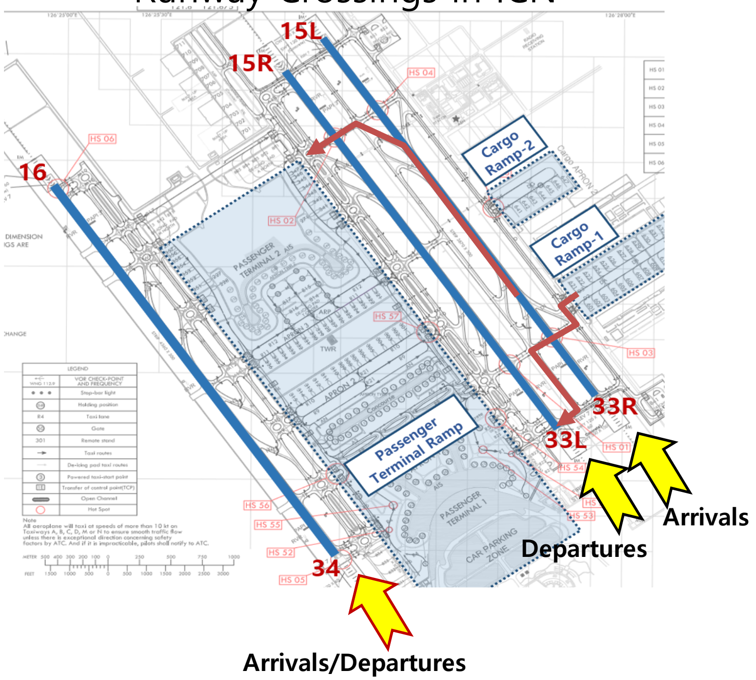
Summation of Delay Times



Gate Holding = AOBT – TOBT
Taxi Delay = ATOT - UTOT

AOBT: Actual Off-Block Time
TOBT: Target Off-Block Time
ATOT: Actual Take-Off Time
UTOT: Unimpeded Take-Off Time

Runway Crossings in ICN

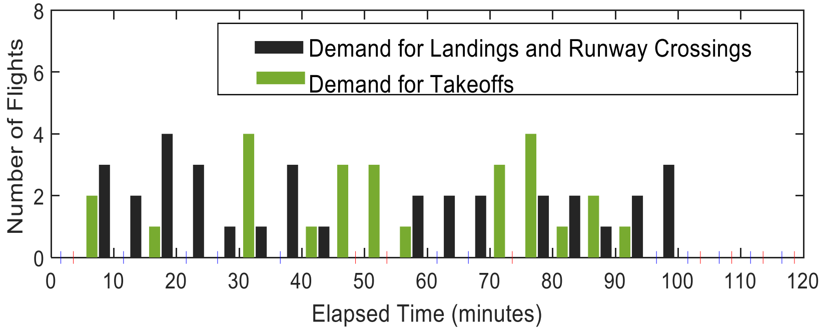


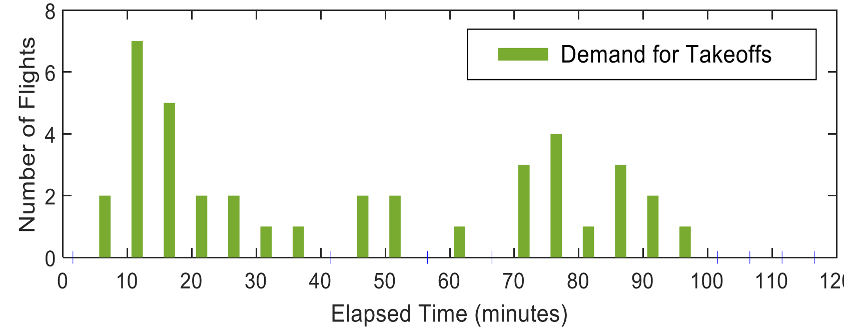
Runway Departure Queue

(RWY 33L)

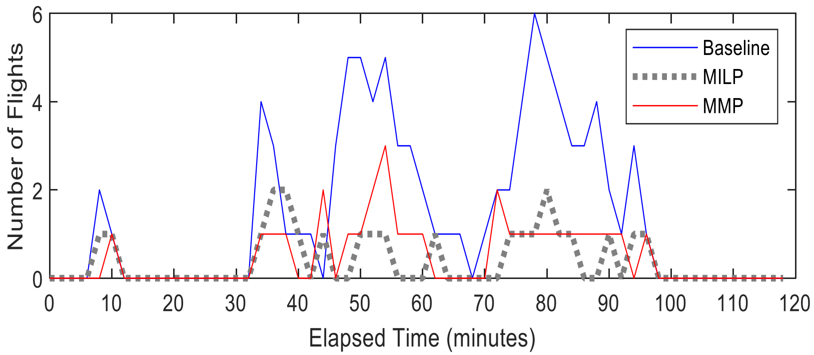
(RWY 34)

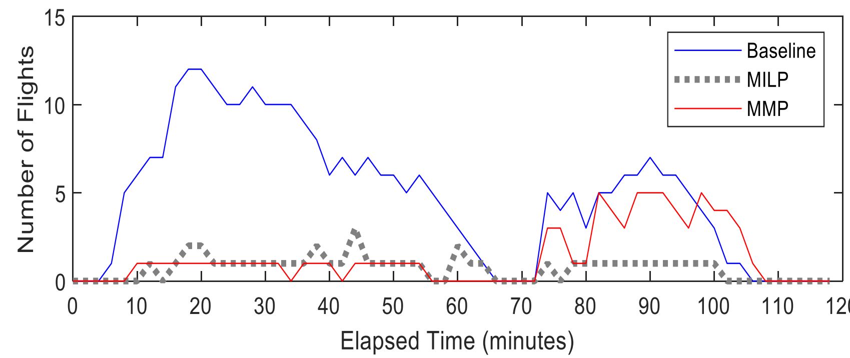
Traffic Demands





Runway Departure Queue

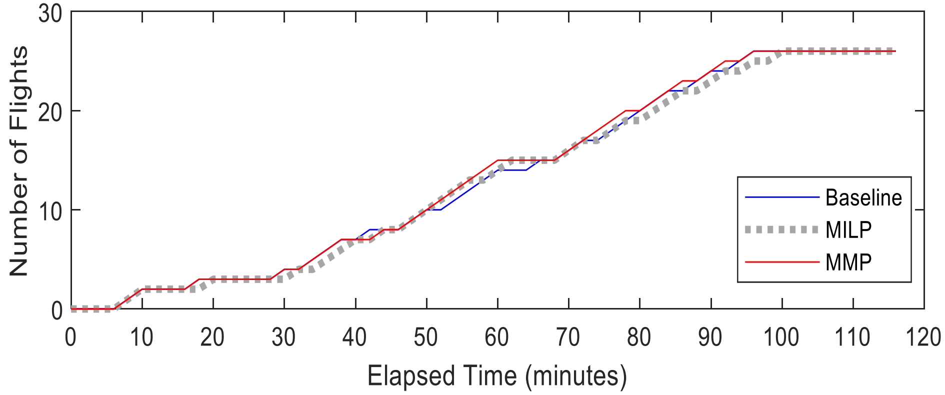




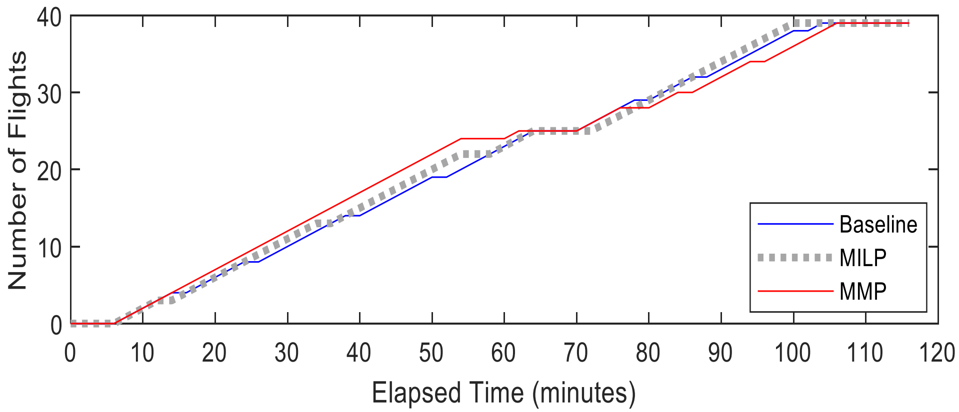
Accumulate Runway Throughputs

Accumulated Runway Throughputs

RWY 33L



RWY 34

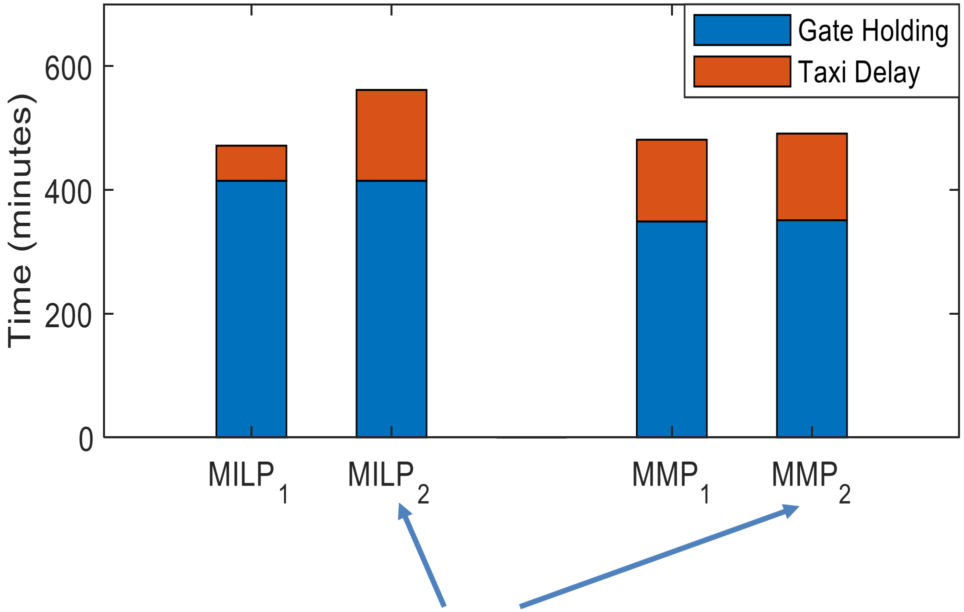


No significant differences in the accumulated throughput curves

→ No runway dry-out

Delay Time Changes by Uncertainties

Delay Time Changes by Uncertainties in Expected Landing Times of Arrival Flights



When uncertainties were given in expected landing times of arrival flights.

As a tactical scheduler, MMP is more robust to the uncertainties due to the frequent scheduling using aircraft current position updates.

Conclusions

- A tactical scheduler for surface metering satisfying MDI restrictions of ICN was developed.
  - Criteria to impose MDI restrictions to a departure flight were formulated into a software readable table form.
  - A greedy style heuristic algorithm was developed to provide departure schedules.
- The performances of the proposed tactical scheduling algorithm was compared with current day operation and MILP-based optimal schedule.
  - Scheduling performance comparisons were conducted through fast-time simulations.
  - Delay times, departure queue lengths were decreased by the proposed algorithm.
  - Compared to the MILP-based optimal schedule, the tactical scheduler showed reasonable performance with the robustness against traffic uncertainties.
- Due to its computational efficiency compared to the MILP approach and robustness, the proposed heuristic scheduling algorithm appears to be a good candidate for real-time implementation such as MIDAS.

Conclusions

- As a future work, the scheduling performance will be continuously validated and evaluated through the analysis of data gathered in shadow mode operations of MMP at ICN.

Backup Slides

Research Backgrounds

- Since 2014, KARI (Korea Aerospace Research Institute) has been conducting a research project, **MIDAS (Management on Integrated operations of Departure, Arrival and Surface traffic)**.

- Since 2017, ICN(Incheon International Airport) has started to implement Airport-CDM.

- In 2017, IIAC (Incheon International Airport Cooperation) and KARI signed an agreement to work together towards **developing and testing new surface metering capabilities**.

  - Providing A-CDM information sharing system with **the enhanced TTOT/TSAT to support the TMIs (CTOT and MDI restrictions)**.

- In 2018, KARI installed a prototype decision support tool developed in the MIDAS project in the ATC tower and the ramp tower of ICN

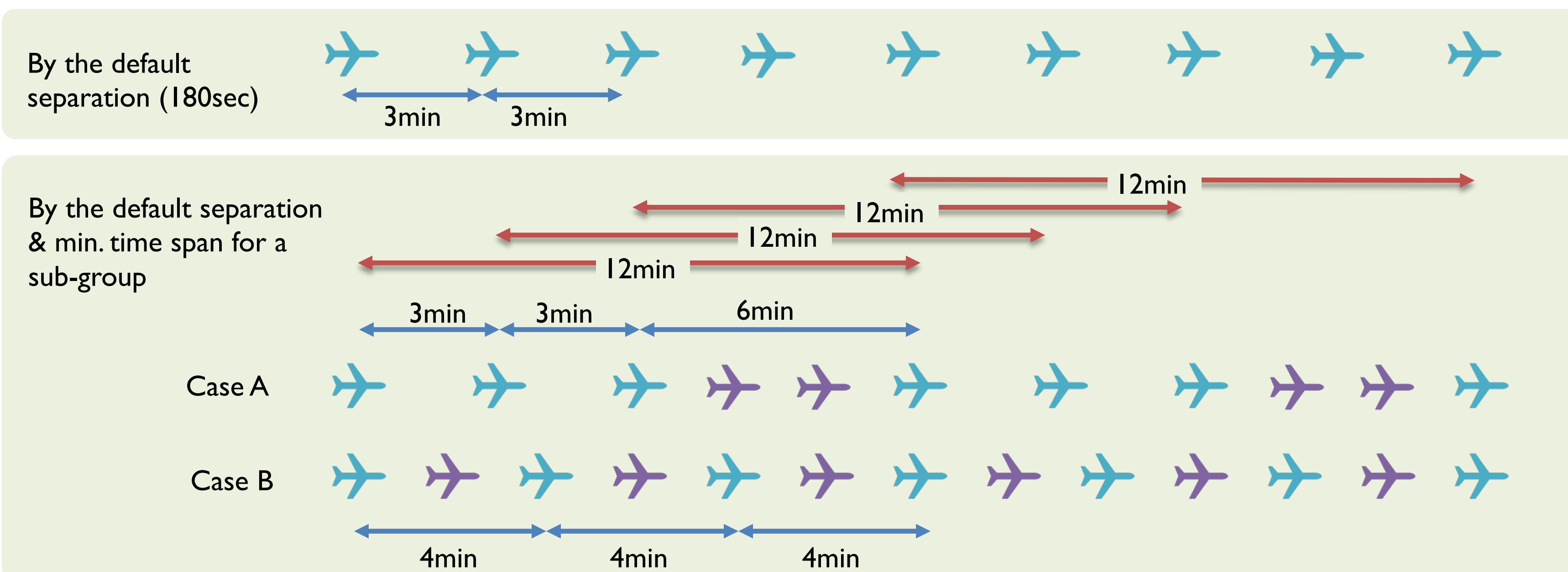
  - The prototype decision support tool is "**MMP (MIDAS Main Processor)**".

Sub-group Conditions in MDI

	Conditions						Separation Requirement				Activation Schedule	
MDI Name	Destinations				FIR Exit Fix	Route	Default		For a Sub-group		StartTime (UTC)	EndTime (UTC)
	Flight A		Flight B									
	Area	Airport Code	Area	Airport Code			Type	Value (sec)	Pattern	Min. Time Span (sec)		
Default_21	N. America		N. America		LANAT		TIME	180	D-D-D-D	720	11:00	23:00
Default_22	N. America		N. America		ANDOL		TIME	180	D-D-D-D	720	11:00	23:00
Default_23	N. America		N. America		KANSU		TIME	180	D-D-D-D	720	11:00	23:00

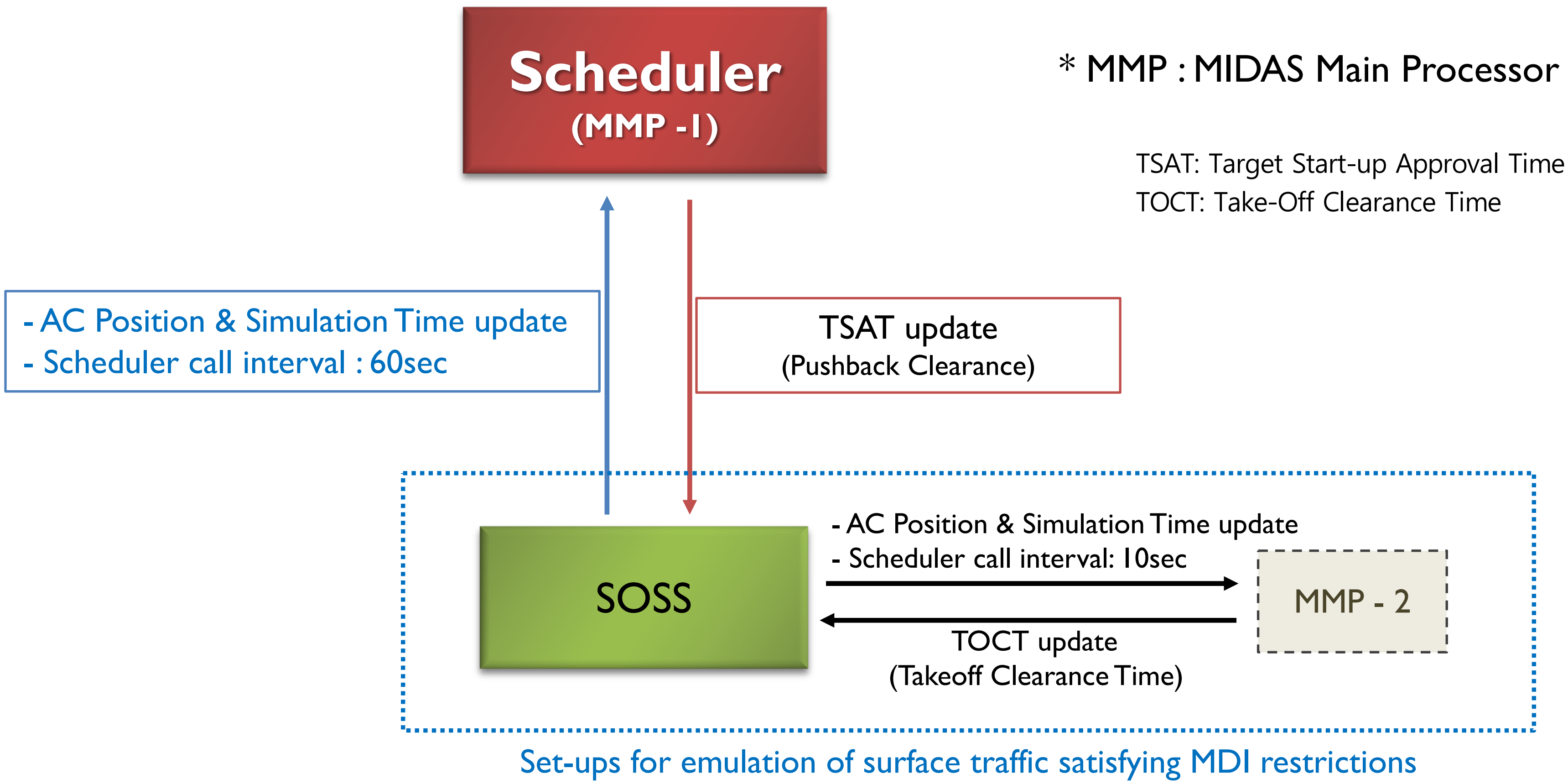
Departure aircraft going to North America

Departure aircraft not going to North America



Algorithm Evaluation based on Fast-time Simulation

Set-ups for Fast-time Simulation



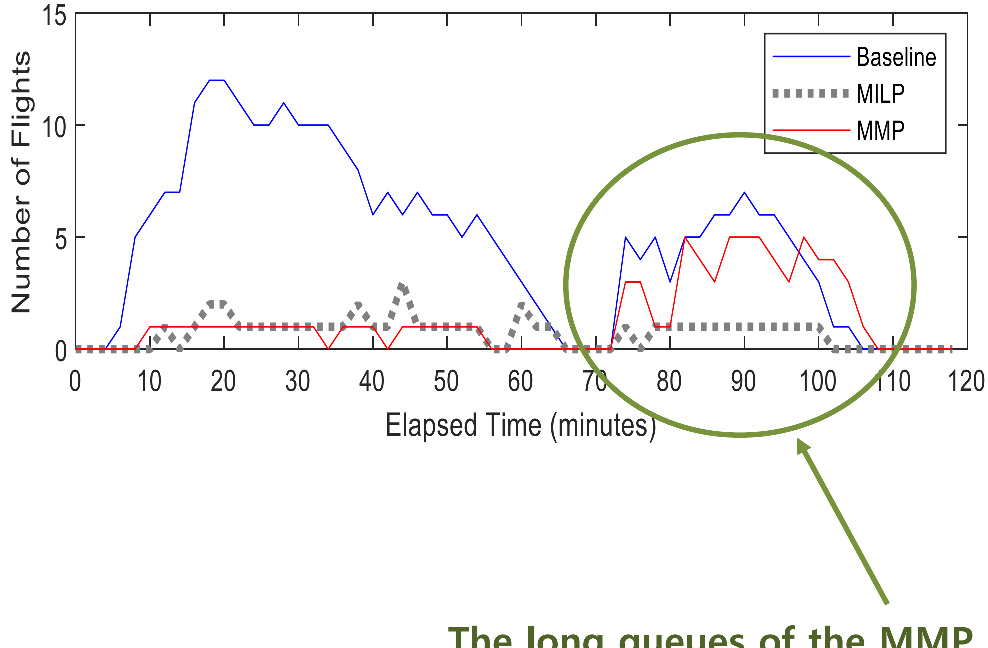
- MMP-1: A surface metering scheduler providing TSATs.
- MMP-2: Part of the simulation tool that ensures aircraft takeoff meets the MDI restrictions.

Algorithm Evaluation based on Fast-Time Simulation

What we are comparing for the results

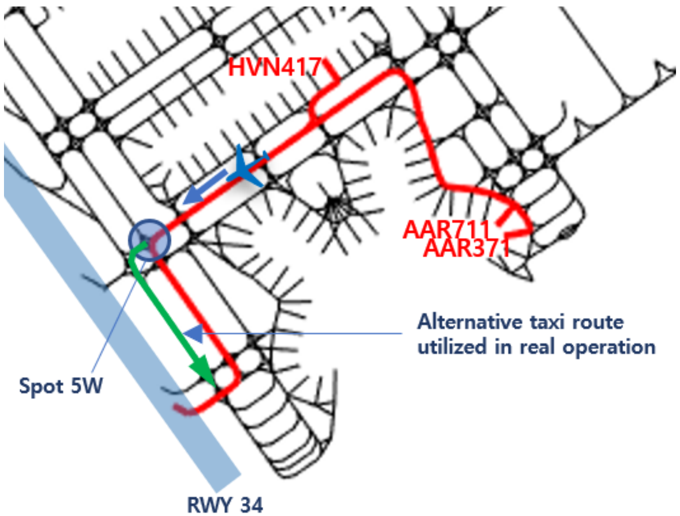
	MMP-1 (Scheduler)	MMP-2	Stands for
Baseline	Not used	Used	Current day operation
MILP	Used (TSATs from the scheduler are the optimization results of MILP-based models for runway and taxiway scheduling.)	Used	Optimized schedule for minimizing the total taxi delay times (as strategic pre-departure scheduling)
MMP	**Used**	**Used**	**A tactical scheduler**

Inconsistency of the Queue Length of the MMP Case



The long queues of the MMP case – why?

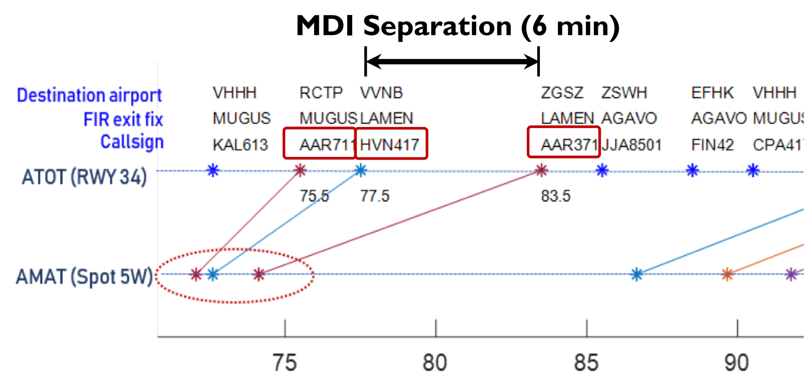
Inconsistency of the Queue Length of the MMP Case



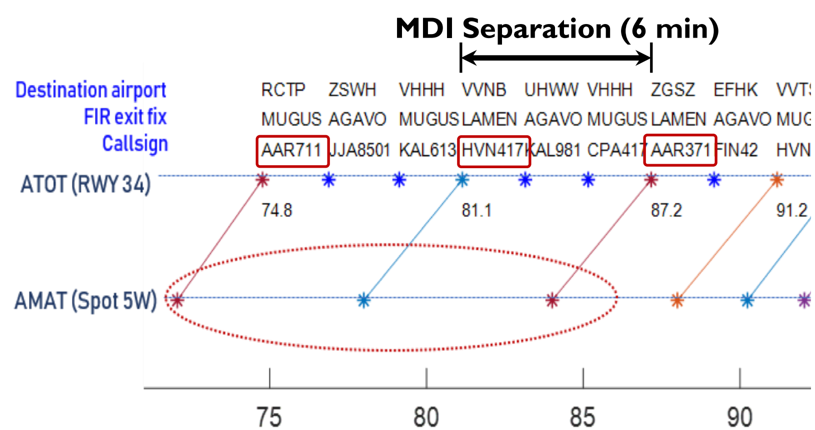
Taxi Routes of 'HVN417', 'AAR711', and 'AAR371'

- In the simulation, spot passing sequence = takeoff sequence
- In real-world operation, spot passing sequence ≠ takeoff sequence by using the alternative taxi route (letting the aircraft make multiple queues.)

AMATs (Actual Movement Area entry Times) and ATOTs

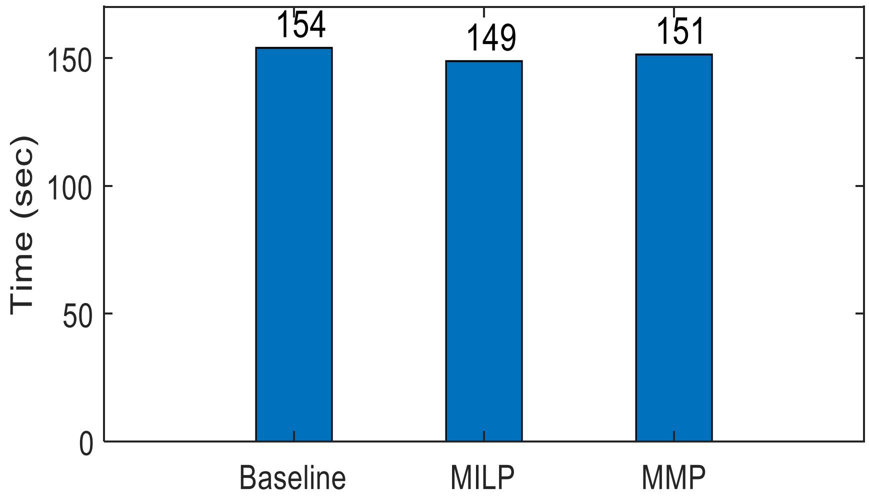


<MMP case>



<MILP case>

Average Separation between Takeoffs



(RWY 34)

Separation (= difference of ATOTs of two consecutive departures) : except for the 'no departure queue' cases when the following aircraft took off without waiting in the departure queue.

The separations were slightly reduced by the changes in takeoff sequences of both MILP and MMP.