Simulation-Free Runway Balancing Optimization Under Uncertainty Using Neural Network

9 th SESAR Innovation Days

Ryota Mori (ENRI)

Daniel Delahaye (ENAC)

Runway balancing problem

- Runway balancing is a powerful method to minimize delay and maximize capacity at multi-runway airports.
  - Can be a part of AMAN/DMAN.
    - This research focuses on arrival traffic only.
  - Easy to solve if no uncertainty exists.
    - General combinatorial optimization

    ➔ In real world, considerable uncertainty exists.

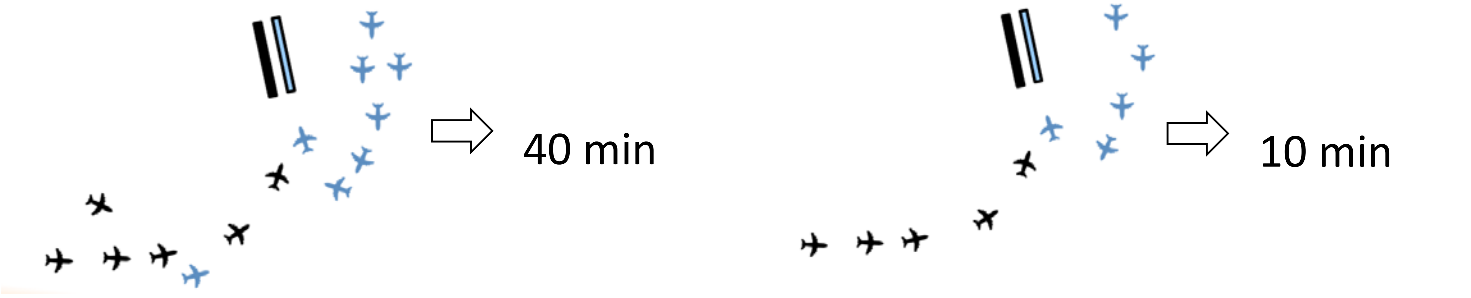
Several methods for runway balancing

- To solve runway balancing problem:
  1) Delay of aircraft is estimated.
  2) Optimal solution is found.
- Several approaches to estimate delay
  - Conventional queueing method (e.g. Kendall notation such as M/M/1)
    - Only simple runway operation can be assumed.
  - Simulation-based optimization method
    - Detailed dynamics can be considered by incorporating them into simulation.
    - Accuracy of simulation model affects the system performance.
  - Simulation-free optimization method
    - Data-based optimization method: real world data is directly used to estimate the delay, and no simulation model is needed in the optimization process.

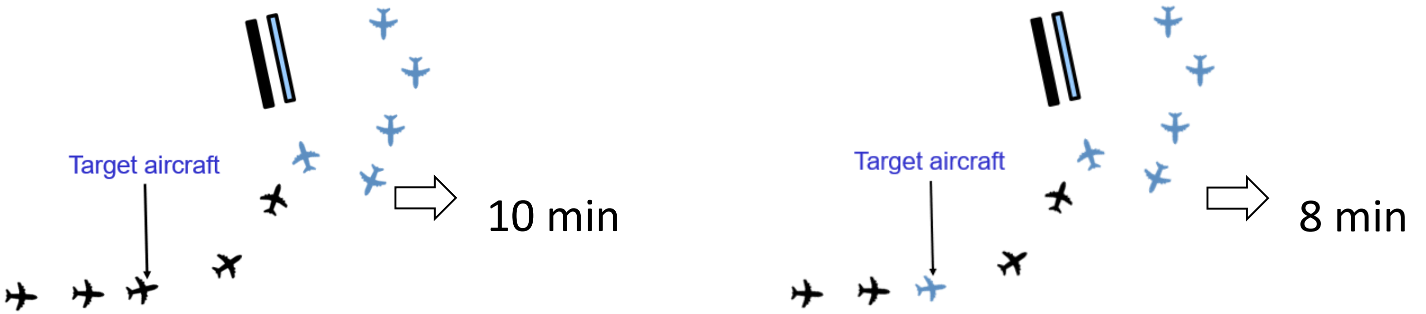
➔ This research uses neural network (NN) to estimate aircraft delay.

NN-based simulation free optimization method

1) Relationship between the current traffic pattern and the sum of the extra flight time (ALDT–ELDT) of all aircraft (= total delay) is modeled by NN.



2) NN is used as a delay predictor to find the best solution.

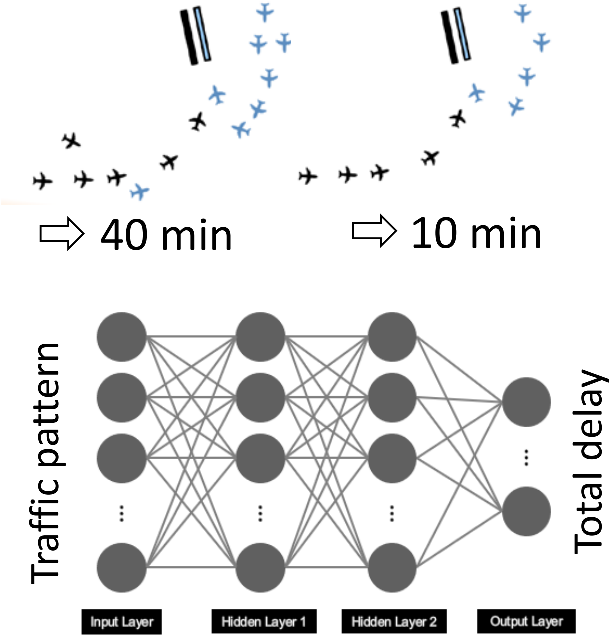


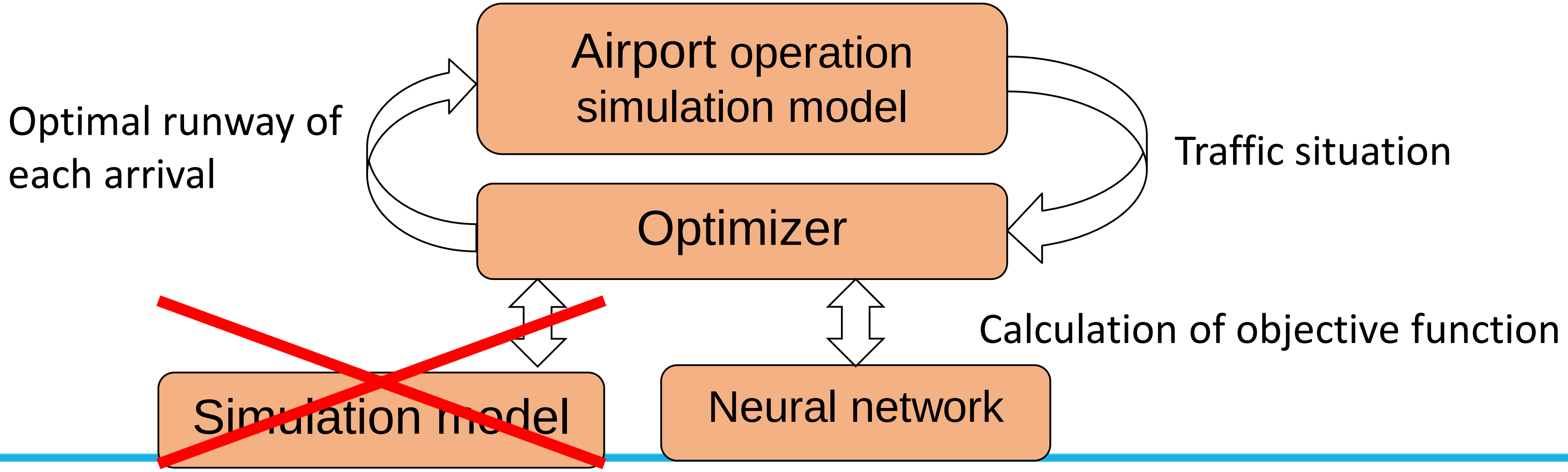
Better to change the runway.

Research flow

- To validate the proposed method, data is generated via simulations, and the proposed method is evaluated.
  - Simulation model is used for data generation and evaluation purpose only. (Optimization process does not use simulation model.)

1) Multiple simulations are conducted to generate input/output data.
2) NN model is developed using generated data.
3) Optimal runway assignment strategy is found using NN model.
4) The optimal strategy by NN is evaluated using the simulation model.



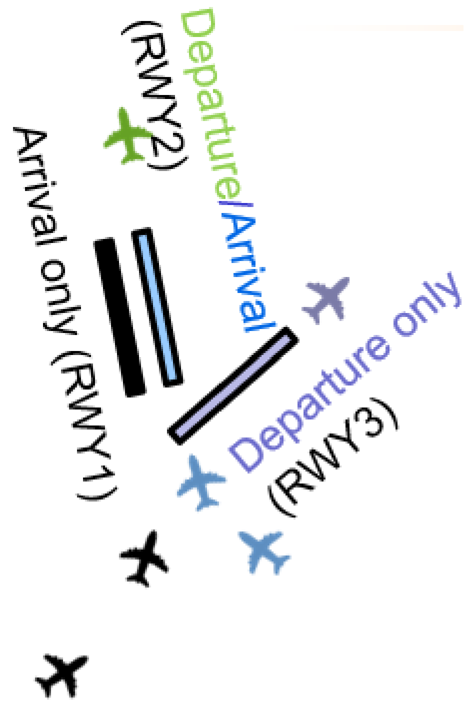


Advantages of the proposed method

- Simulation model is not required to find the optimal solution.
  - It is sometimes very hard to simulate the details of traffic flow.
- Airport operational uncertainty and ATC operational rules are automatically learned by NN.
  - NN is trained to minimize the error of the delay.
    - The expected value of delay under uncertainty will be obtained.
    - No explicit consideration of uncertainty is needed.
  - NN models the delay regardless of complicated ATC operational rules.
    - The data include all operational characteristics.

Simulation scenario (1)

- Baseline scenario
  - Arrival-only (RWY1), and mixed-mode (RWY2), mixed-mode(RWY2/3).
  - Traffic demand
    - Arrival & Departure hourly throughput: 15-35 aircraft/hour each
    - Ratio of nominal arrival RWY1: 75-95%
    - Ratio of nominal departure RWY2: 40-60%
    - ETOT/ELDT is randomly distributed throughout time.
  - Separation
    - All separations (Departure/Arrival – Departure/Arrival): 2 minutes
  - Uncertainty
    - Departure ETOT: 5 minutes of SD
    - Arrival ELDT: 2% of remaining flight time of SD
    - Take-off/landing separation: 15 s of SD
  - Runway swap cost
    - 2 minutes additional flight time
    - No swap is expected when there is no congestion.
  - Runway swap is possible for arrival aircraft only.



Simulation scenario (2)

- Decision variables

$$\delta_i = \begin{cases} 1 & r_i \neq r_i^{nom} \\ 0 & otherwise \end{cases} \quad \forall i \in A$$

  - Arrival runway must be decided 30 minutes before landing (ELDT).

- Objective function

$$J = \sum_{i \in D} \left(\underline{ATOT_i - ETOT_i} \right) + \sum_{i \in A} \left(\underline{ALDT_i - ELDT_i} + \underline{\alpha \delta_i} \right)$$

Departure delay cost — Arrival delay cost — Runway swap cost

3	0	2	0	2	2	2	0	0	0	2	2	1	2	1	0	2	0	1	2

Input data representation

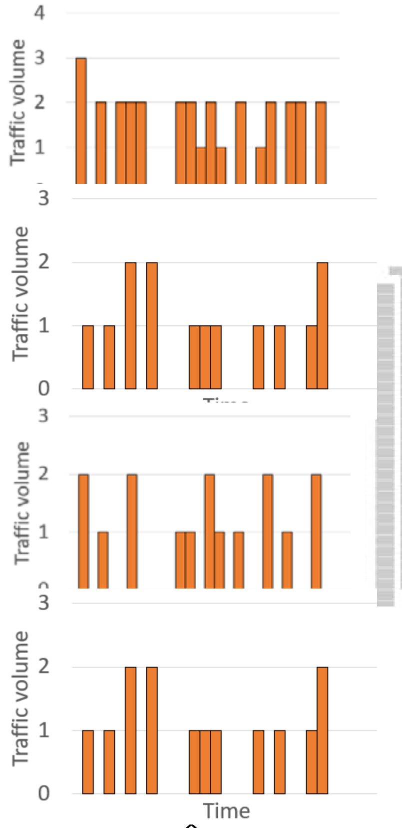
NN model development

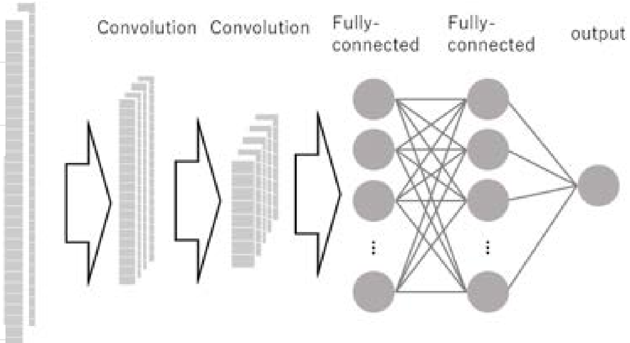
RWY1 (arr)

RWY2 (arr)

RWY2 (dep)

RWY3 (dep)



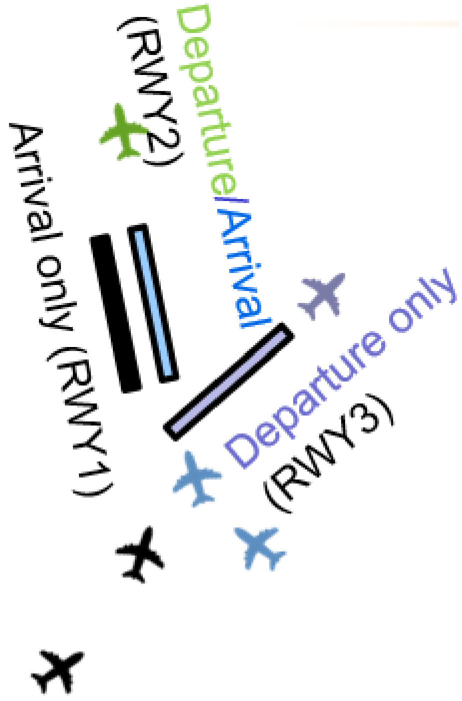


RWY1(arr) waiting time
(= 60 minutes)

RWY2(arr) waiting time
(= 100 minutes)

RWY2(dep) waiting time
(= 80 minutes)

RWY3(dep) waiting time
(= 80 minutes)



Traffic demands

Inputs (ETOT/ELDT)

Outputs

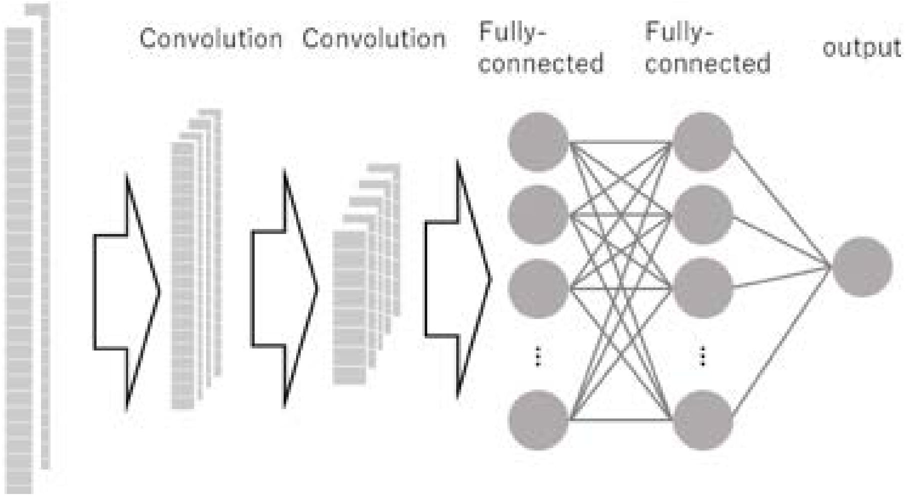
Delay

Many data are generated by simulation this time.

Convolutional NN (CNN)

- CNN connects near nodes only
  - CNN reduces the degree of freedom compared to fully-connected feedforward NN
  - Famous application of CNN is image processing.
- Aircraft delay estimation: a single aircraft affects near aircraft, and propagates the delay to other aircraft.

➔ CNN is appropriate for modeling in this research.



Number of data required

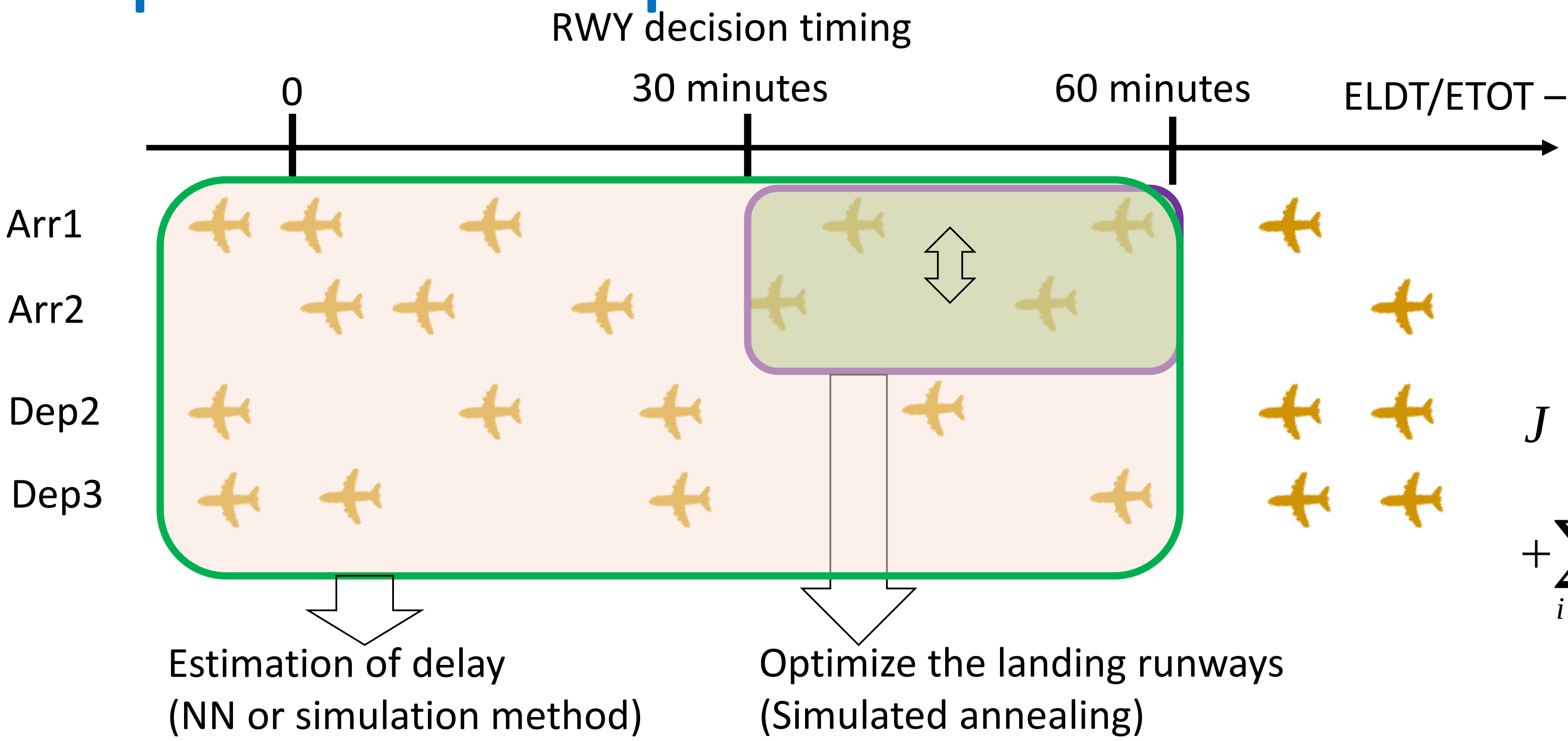
- If implemented in real world, yearly data is the maximum possible data obtained.
  - 60 minutes * 16 hours * 365 days = 350,400
    - Every minute data is used as a single data set.
  - 350,400 data is not enough for NN training according to pre-calculation.
- Data augmentation technique is used to increase the number of data for training.
  - Slight change of input without changing output is used as another set of data.
  - Using 300,000 original data, and 9 times augmentation are done (2,700,000). In total, 3,000,000 data are used for training.

Inputs (Traffic demand) — Output (Total delay)

3	0	2	0	2	2	2	0	0	0	2	2	1	2	1	0	2	0	1	2	150.0
3	0	2	1	1	2	2	0	0	0	2	2	1	2	1	0	2	0	1	2	150.0

One aircraft demand is assumed to shift to the next time slot.

Optimization process



$$J=\sum_{i\in D}\left(ATOT_i-ETOT_i\right)+\sum_{i\in A}\left(ALDT_i-ELDT_i+\alpha\delta_i\right)$$

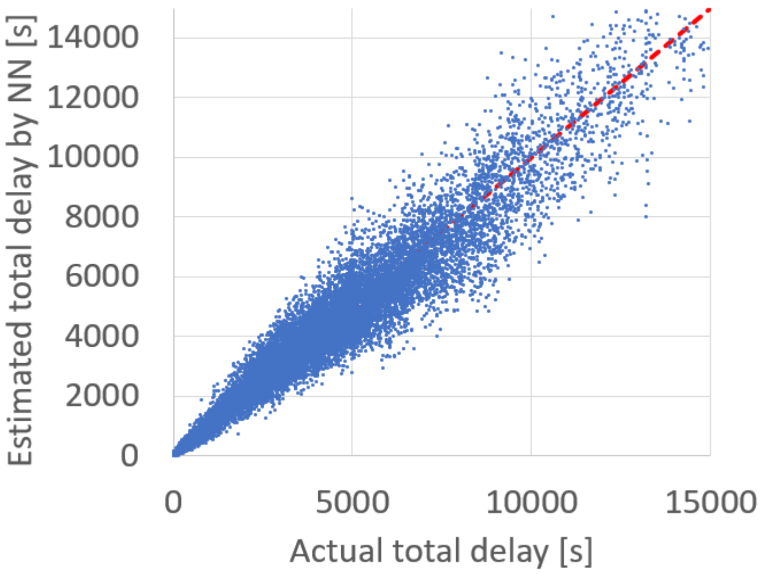
- Optimization is done every 10 minutes.
- The latest result of the optimization is used for arrival runway assignment.

Comparison method

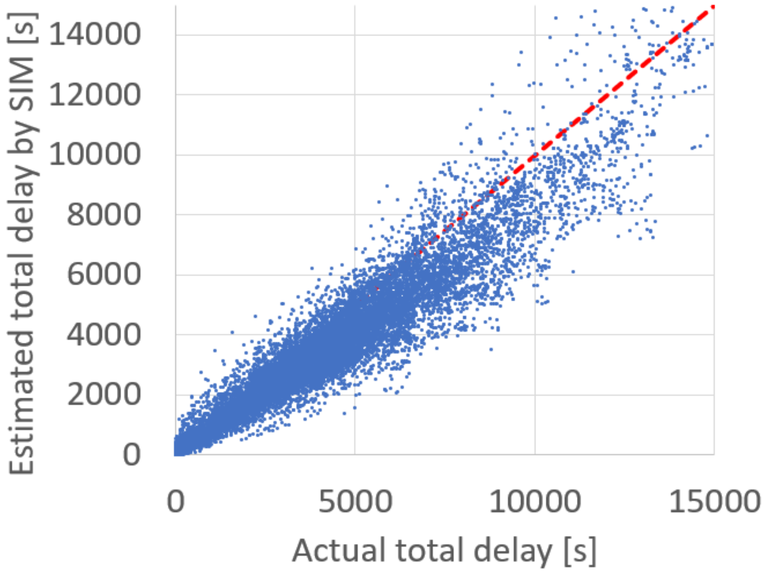
- SIM method
  - Run a simulation without considering uncertainty to estimate the delay.
    - The simulation model is the same as the one used for evaluation.
  - All parameters (e.g. take-off separation) are assumed to be known.
    - This assumption is advantageous for SIM method.
- Optimization process
  - The same optimization method (simulated annealing is used) for both NN method and SIM method.
    - The difference is found in the delay estimation only.
- NN method is expected to estimate the total delay considering uncertainty, which improves the runway balancing optimization.

Estimation results (arrival)

- The delay is well estimated because uncertainty of arrival time is small.
- SIM method underestimates the total delay.
  - Due to uncertainty
  - Supported by queueing theory



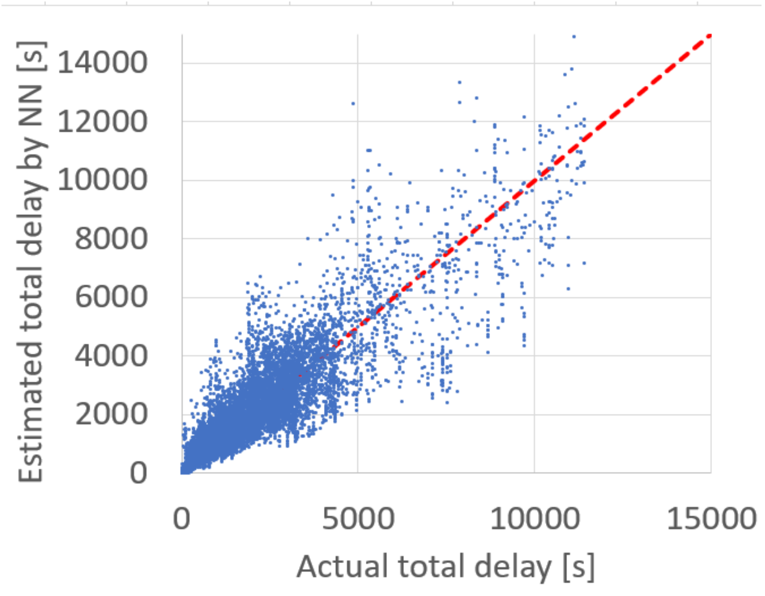
NN (RMSE = 809s)



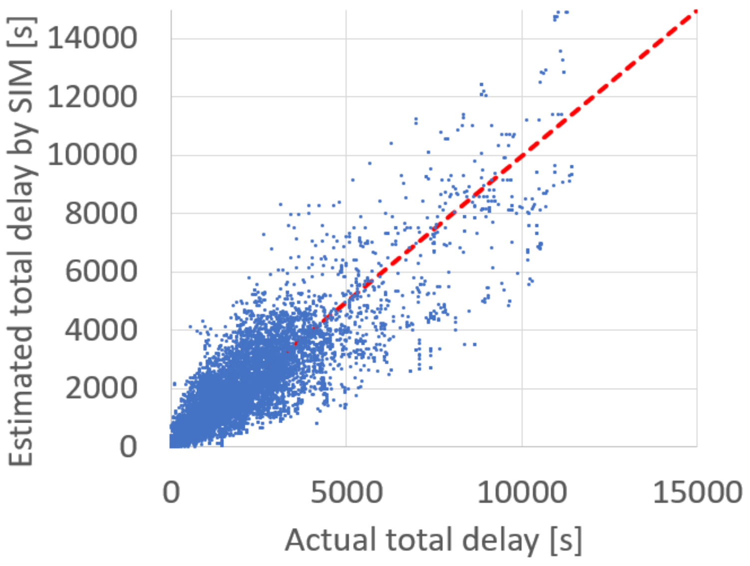
SIM (RMSE = 1122s)

Estimation results (departure)

- The delay is poorly estimated due to large uncertainty of departure.
  - NN estimates the error more accurately.

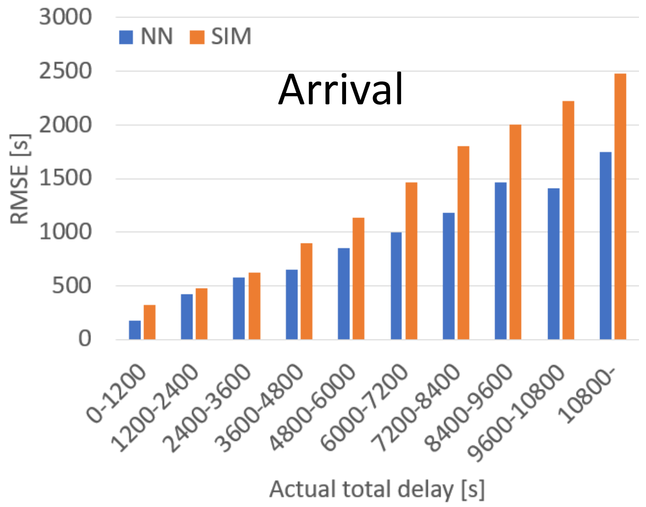


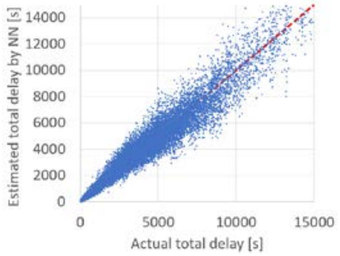
NN (RMSE = 927s)

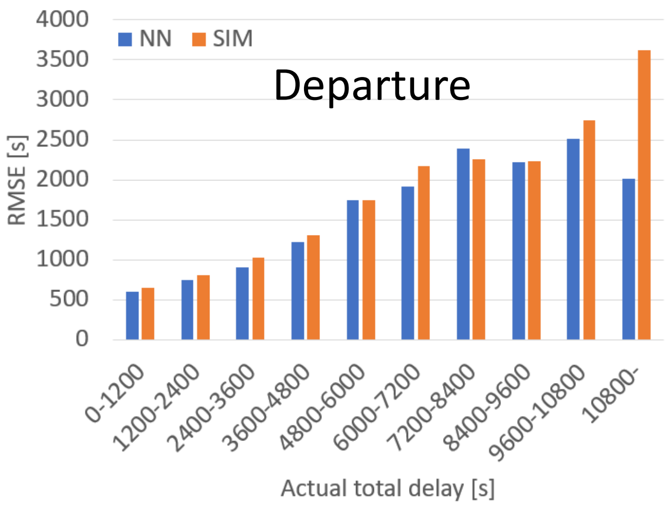


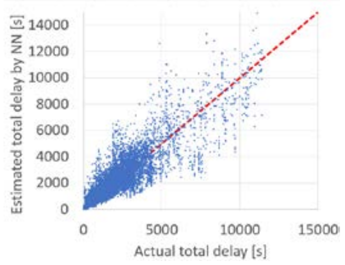
SIM (RMSE = 1009s)

Trend of estimated delay



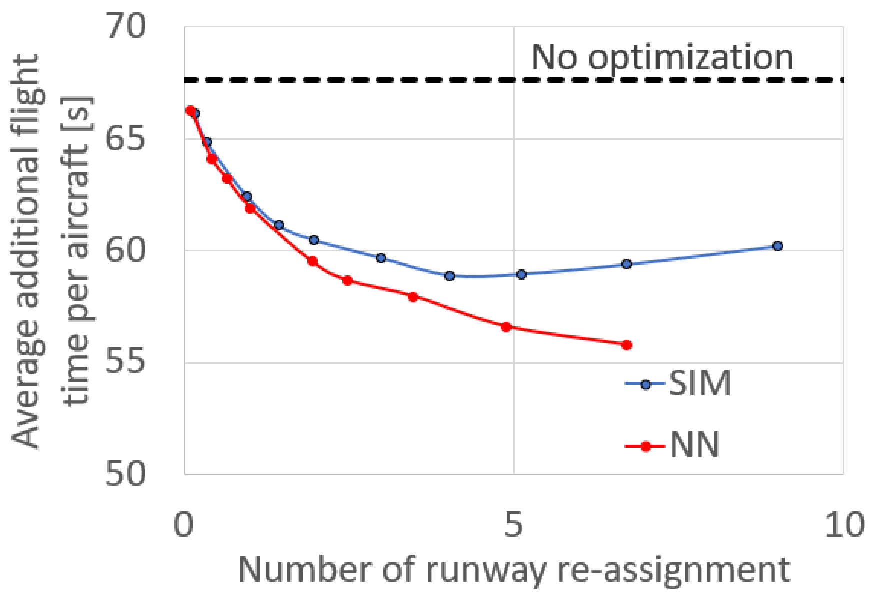




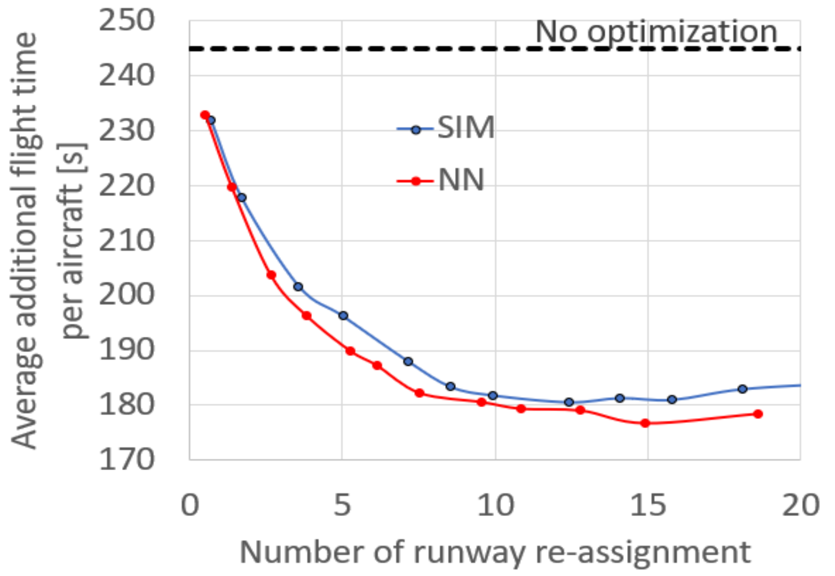


- In general, RMSE increases with delay.
  - As for arrival, NN always estimates the delay better than SIM method.
  - As for departure, NN sometimes estimates the delay worse than SIM method.
    - There is not enough data when the delay is large.

Simulation results (100 times simulation average)



Low traffic (20 aircraft/hour)



Heavy traffic (32 aircraft/hour)

- NN performs better than SIM method.
  - The flight time estimation by NN works well.
- The benefit is relatively greater with low traffic.
  - With heavy traffic, the possible action might be limited.
- The uncertainty affects the performance when the number of runway swap is large.

$$J = \sum_{i \in D} \left(ATOT_i - ETOT_i \right) + \sum_{i \in A} \left(ALDT_i - ELDT_i + \alpha \delta_i \right)$$

Summary

- This research proposes a new simulation-free runway balancing optimization method using NN.
  - NN is used as a delay predictor (calculation of objective function).
- The proposed model shows a better performance than simulation-based method.
  - The simulation-based method is assumed to know all information in advance except uncertainty.
- Future works
  - Further improvement of the proposed method
  - Assumption of more complicated runway operations
    - Further advantage of the proposed method will be expected.
  - Use of less data sets
  - Use of real operational data