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Optimization of Airport Surface Traffic: A Case-study of Incheon International Airport

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This study aims to develop a controllers decision support tool for departure and surface management of ICN. Airport surface traffic optimization for Incheon International Airport (ICN) in South Korea was studied based on the operational characteristics of ICN and airspace of Korea. For surface traffic optimization, a multiple runway scheduling problem and a taxi scheduling problem were formulated into two Mixed Integer Linear Programming (MILP) optimization models. The Miles-In-Trail (MIT) separation constraint at the departure fix shared by the departure flights from multiple runways and the runway crossing constraints due to the taxi route configuration specific to ICN were incorporated into the runway scheduling and taxiway scheduling problems, respectively. Since the MILP-based optimization model for the multiple runway scheduling problem may be computationally intensive, computation times and delay costs of different solving methods were compared for a practical implementation. This research was a collaboration between Korea Aerospace Research Institute (KARI) and National Aeronautics and Space Administration (NASA).

I. Introduction

Incheon International Airport (ICN) in South Korea is undergoing steadily increased demand for aircraft movements, with more than 5% increase per year in the past six years. Various airport operational improvements, including adding a new passenger terminal and implementation of A-CDM (Airport – Collaborative Decision

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Making[1]) are under progress in ICN, and there has been a need for a system to integrate departure and surface traffic management for full implementation of A-CDM at ICN. Scheduling algorithms are the core components of such a system for both tactical or strategic departure and surface management, and the surface traffic optimization must appropriately incorporate the requirements specific to ICN operations, such as the Traffic Management Initiatives (TMIs), runway/taxiway configuration, and runway assignment strategies.

A. Surface Traffic Optimization

Surface traffic optimization has been studied for decades in many research areas. There are several studies, in which whole surface movements of aircraft including taxi-in and out, landings, and take-offs were integrated into a single optimization problem. This approach is referred to as the 'integrated model.' [3-5,18,19] On the other hand, the same objective has also been pursued by dividing the optimization problem into two parts: runway scheduling and taxiway scheduling, which is referred to as 'separated models.' [3,4,6-17] The separated models of runway scheduling and taxiway scheduling are linked through common requirements, such as earliest possible pushback ready times and target take-off sequence and times. Comparisons of these two approaches were also investigated[3,4]. The objective of the runway scheduling problem is to determine the optimal take-off/landing/crossing sequence and times for the maximum runway throughput, while the taxiway scheduling problem is to determine the optimal push-back times or spot release times for minimizing taxi-out times. In most of the cases, the target take-off times are determined through runway scheduling first, and then they are utilized as inputs in taxiway scheduling. This sequential scheduling method has been incorporated in NASA's Spot and Runway Departure Advisor (SARDA) concept.[23]

In the surface traffic optimization problem for ICN, both optimal take-off times for runway throughput improvement and optimal push-back times for taxi-out time reduction should be obtained and provided to the ramp and air traffic control tower controllers. Therefore, both runway scheduling and taxiway scheduling should be integrated into the surface traffic optimization. In this study, the three-step approach[3,4,10,12], which is a generalized concept of the sequential scheduling method consisting of: 1) unimpeded taxi-out time estimation; 2) runway scheduling for departures; and 3) taxiway scheduling, was applied. The development and test of the optimization model used for Step 2 and 3 are described in this paper.

B. Runway Scheduling Problem

The runway scheduling problem has been studied in various ways. In particular, many common solution techniques used for job-shop scheduling problems, such as dynamic programming[9,11,20,22], heuristics[24], as well as Mixed Integer Linear Programming (MILP)-based optimization model[3,4,13,8,10], were applied to runway scheduling problems. Ref. 10 indicates that most previous studies focused on a single runway scheduling problem, whereas a multiple runway scheduling problem[10] should be considered for runway scheduling in ICN, due to the specific TMI constraint that affects take-offs from two departure runways (see Section II).

C. Taxi Scheduling Problem

The taxi scheduling problem is usually formulated by using a node-link model, a graphical expression of the taxiway configuration. It aims to determine the sequence and times of aircraft passage at each node on the taxi routes for the minimum taxi times of the aircraft with considerations of operational and safety related constraints.[3-5, 12-14, 17-19] In previous studies by Balakrishnan[12], Frankovich[13], and Lee[21], time was discretized into uniform intervals, and the decision variables for the taxiway scheduling were given as binary variables to decide whether a specific event, such as a pushback or aircraft arrival at a node, occurs or not in each time granularity. In other studies, the decision variables are given as continuous variables for the aircraft passage times at nodes, and binary variables to determine the aircraft passage sequence at intersection nodes[3-5,14,19]. The taxi routes for the aircraft were assumed to be predetermined in most approaches[12-14,21], but sometimes the changes of taxi routes for conflict avoidance at intersections were also considered in the MILP-based models[19]. This problem could also be modeled as a job-shop scheduling problem[17] and solved by algorithms such as genetic agorithm[15,16] and greedy heuristics[15].

The airport surface traffic optimization for ICN described in this paper is accomplished by introducing requirements and relevant assumptions based on the operational characteristics of ICN identified in prior work[2]. MILP is used for both runway scheduling and taxi scheduling. In development of the runway scheduler, NASA's MILP-based optimization model for Charlotte Douglas International Airport[10] is used with some modifications of constraints to deal with the TMIs of ICN. In taxi scheduling, runway crossing constraints are incorporated into the MILP formulation, considering the taxiway configuration of ICN.

This study is conducted as part of the research collaboration between Korea Aerospace Research Institute (KARI) and National Aeronautics and Space Administration (NASA) in the area of the Integrated Arrival, Departure, and Surface (IADS) management.

This paper is organized as follows. The scheduling requirements for surface traffic optimization in ICN are described in Section II. Based on the requirements, MILP-based optimization models for runway scheduling and taxiway scheduling are presented in Section III and IV, respectively. In Section V, optimization results of a single scenario are shown first, then a Monte-Carlo-based optimization test results using multiple scenarios are presented and discussed to compare computational tractability and cost performance. Lastly, Section VI provides concluding remarks and briefly discusses future research plans.

II. Scheduling Requirements

ICN has three parallel runways and two ramp areas separated by RWY 33L/15R and 33R/15L as shown in Fig. 1. The Main Ramp is used only for passenger planes, and the Cargo Ramp is used for freighters. All freighters take off and land using RWY 33L/15R and 33R/15L, respectively. While the usage of RWY 34/16 changes several times a day according to the arrivals and departure demand at ICN, RWY 33L/15R and 33R/15L are exclusively used for departures and arrivals, respectively. Since these two parallel runways are separated by a distance of 400m, the same wake turbulence runway separation rules used for a single runway with mixed mode operation are applied[2]. The runway crossings on both runways also need to be considered. All passenger planes landing on RWY 33R/15L must cross RWY 33L/15R before entering the Main Ramp area, and all departure freighters from Cargo Ramp must cross RWY 33R/15L to take off from RWY 33L/15R.

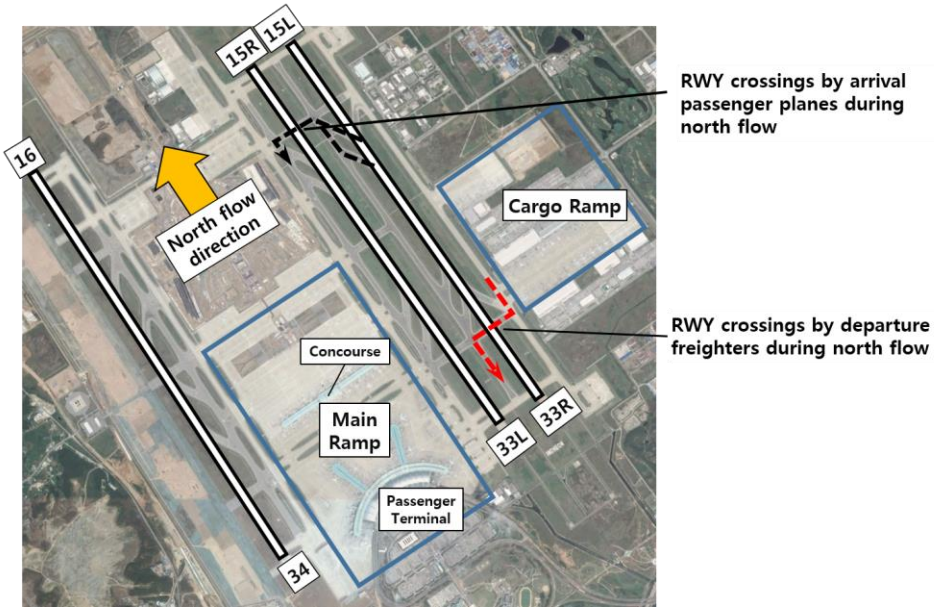

Figure 1. Airport configuration of ICN

Therefore, the runway crossings of both arrival passenger planes and departure freighters are dependent on each other from a runway scheduling point of view. The runway crossing of arrival passenger planes should be taken into account for departure scheduling, while the runway crossing of departure freighters should be considered in arrival scheduling. In addition, departure and arrival schedules on both adjacent runways RWY 33L/15R and 33R/15L should meet the wake turbulence separation requirements as if they are operating on a single runway. Assuming that landing times of arrival flights are given, however, we can separate the runway crossings. If the runway arrival times are not adjustable, runway crossings by departure freighters can happen whenever there is a gap between landing aircraft. Since there is no runway separation requirement between a take-off on RWY 33L/15R and a runway crossing on RWY 33R/15L, the runway crossings on the arrival runway (RWY 33R/15L) by freighters do not need to be considered in runway scheduling. On the other hand, taxi-out time extension due to arrival runway crossings by departure freighters should be considered, and the relative order of runway crossings of freighters should be the same as that of take-offs. In this study, departure runway crossings by arrival passenger flights were incorporated in the runway scheduling, whereas the arrival runway crossings by departure freighters were taken into account in the

taxiway scheduling. Details of the formulation of the runway and taxi scheduling will be presented in Section III and IV, respectively.

As depicted in Fig. 2, there are four departure route directions from ICN: west, south, southeast, and east. According to the ICN operational data analysis results[2], departures bound for west and south directions make up most of the total departure demand of ICN. RWY 34/16 is exclusively used for west and south bound departures during the departure demand peak hours, while some of the west or south-bound departures (for example, the freighters bound to west and south) take off from RWY 33L/15R and merge at the shared departure fixes with the departures from RWY 34/16 to the west and south-bound routes. Therefore, the runway scheduling needs to take into account the fact that the standard departure procedures from these two runways share the same departure fixes. TMIs, such as a Miles-In-Trail (MIT) restriction, are imposed constantly on the departures to the shared departure fixes, and the MIT separation values may change several times a day according to requests from the adjacent foreign FIR (Flight Information Region) on the westside of ICN, Shanghai FIR.

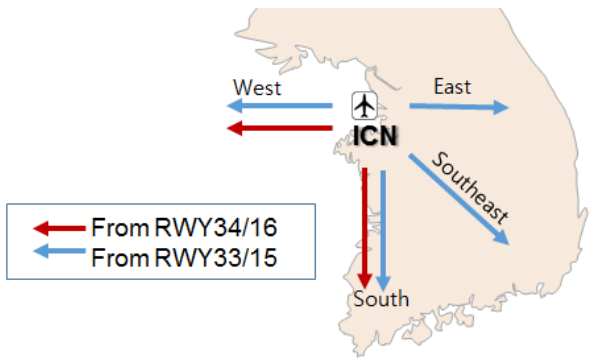

Figure 2. Departure Route Directions

In runway scheduling, various types of TMI restrictions can be considered. MIT or Minimum Departure Interval (MDI) restrictions over certain departure fixes or routes can be incorporated. Expect Departure Clearance Time (EDCT) or Call For Release (CFR) types of restrictions, which involve specific take-off time compliance windows, can also be imposed to certain aircraft. The CFR type of restriction at ICN is called 'On-Time-Departure' and aims to control a CFR flight to a specified target take-off time. The distance from ICN to the Shanghai FIR boarder is 120 NM, and it is difficult to make the departures merge into the overflight stream smoothly in such a short distance.[2] Hence, several strategies are being considered to overcome these difficulties on the South Korea side of operations. One strategy is to add a new type of TMI, for example, giving information about the available time slots, where a departure aircraft is allowed to merge into the overflight stream avoiding the expected times of the other overflight traffic at the merging fix. Then the potential time slots for take-offs of a departure bound for the merging fix can be obtained with consideration for the transit time to the merging fix from the departure runway. In this study, these potential time slots for take-off of a departure flight are referred to as 'multiple take-off time windows,' whereas the original take-off time window is referred to as 'a single time window.' It is also useful to have a departure arrive at a shared departure fix within one of the given time windows, which might be required for departure metering at a shared departure fix in a metroplex environment.

III. Runway Scheduling

Including the requirements described above, the runway schedule optimization problem has been formulated as a MILP, of which the mathematical expression is given in Eqs (1)-(8).

$$\text{minimize} \quad \sum_{i \in D} \left(t_i - \text{EarliestT}_i \right) \tag{1}$$

$$\text{subject to} \quad z_{ij} + z_{ji} = 1, \quad \forall i, j \in D \cup A \cup C, \; i \neq j \tag{2}$$

$$t_j - t_i - \text{Rsep}_{ij} \geq -M\left(1 - z_{ij}\right), \quad \forall i, j \in D \cup A \cup C, \; i \neq j \tag{3}$$

$$\text{EarliestT}_i \leq t_i \leq \text{LatestT}_i, \quad \forall i, j \in D \cup A \cup C \tag{4}$$

$$t_j - t_i + \left(\mathrm{TransT}_j^k - \mathrm{TransT}_j^k - \frac{\mathrm{MIT}_k}{\mathrm{TransV}_i^k} \right) \geq -M\left(1 - z_{ij}\right), \quad \forall i, j \in D_{MIT_k},\ i \neq j \tag{5}$$

$$\mathrm{MinTime}_{i,k} - M\left(1 - s_i^k\right) \leq t_i \leq \mathrm{MaxTime}_{i,k} + M\left(1 - s_i^k\right), \quad \forall i \in D_{TimeW} \tag{6}$$

$$z_{ij} = 1, \quad \forall i, j \in D_{Class_k},\ \mathrm{EarliestT}_i < \mathrm{EarliestT}_j,\ i \neq j \tag{7}$$

$$z_{ij} \in \{0, 1\}, \quad \forall i, j \in D \cup A \cup C \tag{8}$$

where *D*, *A*, and *C* denote the set of departure, arrival and runway crossing flights, respectively. It should be noted that the set of crossing flights consists of the arrival passenger flights, which need to cross the departure runway, RWY 33L/15R. Decision variables are the calculated runway usage time of aircraft *i*, t_i $\forall i, j \in D \cup A \cup C$ and the binary variable z_{ij} $\forall i, j \in D \cup A \cup C,\ i \neq j$, that specifies the relative order of runway use between aircraft *i* and *j*.[3] The objective function is the summation of the runway delays as given in Eq. (1), where $\mathrm{EarliestT}_i$ is the earliest possible take-off time of aircraft *i*, $\forall i \in D$. The constraints expressed in Eqs (2)-(4), and (8) are for determination of relative order and runway usage time which maintain the required runway separation between aircraft *i* and *j*, Rsep_{ij}, within the earliest and latest possible runway usage time, $\mathrm{EarliestT}_i$ and $\mathrm{LatestT}_i$. Since there is only one crossing point for RWY 33L/15R crossings by arrival aircraft, the runway crossing sequence should be the same as the arrival sequence on RWY 33R/15L. The $\mathrm{EarliestT}_i$ of aircraft *i* $\forall i \in C$ is given as the earliest possible time to arrive at the crossing point, and $\mathrm{LatestT}_i$ is given as $\mathrm{LatestT}_i \leq \mathrm{EarliestT}_j$ $\forall i, j \in C,\ i \neq j,\ z_{ij} = 1$, since at the crossing entry point only one aircraft can hold at a time. D_{Class_k} in Eq. (7) denotes the set of departures with the same aircraft class, which is categorized by vortex-separation rules of successive departures, and the relative order of departures in the same class as the First-Come, First-Served (FCFS) sequence based on Eq. (7). In Eq. (5), D_{MIT_k} is a subset of D and represents the set of departures bound for a departure fix *k*. TransT_i^k and TransV_i^k denote the transition time to the departure fix *k* and a passing speed at the departure fix *k* of aircraft *i*, respectively. Let MIT_k be the MIT separation at the departure fix *k*. Then, $\mathrm{MIT}_k / \mathrm{TransV}_i^k$ is the required minimum time separation between aircraft *i* and *j* when aircraft *j* is passing the fix *k* after aircraft *i*. In this study, TransT_i^k and TransV_i^k are assumed to be given as constant values according to the standard instrument departure procedure to fix *k*, although uncertainties in these parameters are expected in real-world operations. Eq. (6) represents the multiple take-off time windows constraint of aircraft *i*, where $\mathrm{MinTime}_{i,k}$ and $\mathrm{MaxTime}_{i,k}$ are respectively the lower and upper bound of the *k*-th take-off time window in the set of multiple time windows of aircraft *i*, which are given in Eq. (9).

$$TimeW_i = \{[\mathrm{MinTime}_{i,1}, \mathrm{MaxTime}_{i,1}], [\mathrm{MinTime}_{i,2}, \mathrm{MaxTime}_{i,2}], \cdots, [\mathrm{MinTime}_{i,N_{W_i}}, \mathrm{MaxTime}_{i,N_{W_i}}]\} \tag{9}$$

In Eq. (6), s_i^k is a new binary decision variable to specify the time window, within which aircraft *i* should take off among the multiple take-off time windows given as a set $TimeW_i$. The value of the decision variable s_i^k $\forall i \in D_{TimeW},\ k \in (1..N_{W_i})$ will be determined in Eq. (10), and should satisfy the constraints given in Eqs. (11)-(12).

$$s_i^k = \begin{cases} 1 & \text{if} \quad \mathrm{MinTime}_{i,k} \leq t_i \leq \mathrm{MaxTime}_{i,k} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

$$s_i^k \in \{1,0\}, \quad \forall i \in D_{TimeW},\ k \in (1..N_{W_i}) \tag{11}$$

$$\sum_{k=1}^{N_{W_i}} s_i^k = 1, \quad \forall i \in D_{TimeW} \tag{12}$$

As mentioned previously, the calculated take-off times of departures from both RWY33L/15R and RWY34/16 should be determined to meet the required separation at the shared departure fixes on the west and south-bound departure routes. For this consideration, runway scheduling might be formulated as a single MILP model using appropriate separations between any pair of arrival, departure, and crossing flights on the two runways.[10] In this study, an alternative approach was also applied, where runway operations were scheduled for a certain runway first, and then calculated take-off times of the departures from that runway to the shared departure fix were applied as constraints for the departures from the other runway. In this approach, the two runway scheduling problems should be solved sequentially, and the influence of the departures in the first runway scheduling probem can be easily taken into account in the second runway scheduling problem using the multiple take-off time window constraint expressed in Eqs. (6) and (9). This approach will be referred to as 'sequential optimization' in Section V.

IV. Taxiway Scheduling

The objective of the taxi scheduling problem is to obtain optimal push-back times for departures, which follow the desired take-off times from the runway scheduling results, with consideration of the interactions among all taxi-out and taxi-in aircraft on the surface. For this purpose, the MILP model of taxi scheduling incorporates passage times at all intersections along the taxi routes as decision variables, and also includes appropriate constraints to maintain safe separation among aircraft. The mathematical formulas in Ref. 3, which are shown in Eqs. (13)-(27), were used for this taxi scheduling, and runway crossings on RWY 33R/15L and 33L/15R were incorporated additionally in Eqs. (28)-(31).

$$\text{minimize } \alpha_p\left(\sum_{i\in D, r\in R} \boldsymbol{max}\left[t_{i,r} - \text{DesiredOff T}_{i,r},\ 0\right]\right) + \alpha_d\left(\sum_{i\in D, r\in R} t_{i,r} - \sum_{i\in D, g\in G} t_{i,r}\right) + \alpha_a\left(\sum_{i\in A, g\in G} t_{i,g} - \sum_{i\in A, r\in R} t_{i,r}\right) \tag{13}$$

$$z_{ij}^u \in \{0,\ 1\},\quad \forall i, j \in D\bigcup A,\ \ i\neq j,\ \ u\in I \tag{14}$$

$$t_{i,u} \geq 0,\quad \forall i \in D\bigcup A,\ \ u\in N \tag{15}$$

$$z_{ij}^u + z_{ji}^u = 1,\quad \forall i,j \in D\bigcup A,\ \ i\neq j,\ \ u\in I \tag{16}$$

$$t_{i,v} \geq t_{i,u} + \text{MinTaxiT}_{uv},\quad \forall i \in D\bigcup A,\ \ (u,v)\in E \tag{17}$$

$$z_{ij}^u = z_{ij}^v,\quad \forall i,j \in D\bigcup A,\ \ i\neq j,\ \ u,v\in I,\ \ (u,v)\in E \tag{18}$$

$$z_{ij}^u + z_{ji}^v = 1,\quad \forall i,j \in D\bigcup A,\ \ i\neq j,\ \ u,v\in I,\ \ (u,v)\in E \tag{19}$$

$$t_{j,u} - t_{i,u} - \left(t_{i,v} - t_{i,u}\right)\frac{\text{Dsep}_{ij}}{l_{uv}} \geq -\left(1 - z_{ij}^u\right)M,\quad \forall i, j \in D\bigcup A,\ \ i\neq j,\ \ u\in I,\ \ (u,v)\in E \tag{20}$$

$$t_{j,v} - t_{i,v} - \left(t_{j,v} - t_{j,u}\right)\frac{\text{Dsep}_{ij}}{l_{uv}} \geq -\left(1 - z_{ij}^v\right)M,\quad \forall i, j \in D\bigcup A,\ \ i\neq j,\ \ v\in I,\ \ (u,v)\in E \tag{21}$$

$$t_{j,r} - t_{i,r} - \text{Rsep}_{ij} \geq -\left(1 - z_{ij}^r\right)M,\quad \forall i, j \in D,\ \ i\neq j,\ \ r\in R \tag{22}$$

$$t_{i,r} \geq \text{EarliestOffT}_{i,r},\quad \forall i \in D,\ \ r\in R \tag{23}$$

$$t_{i,g} \geq \text{OutT}_{i,g},\quad \forall i \in D,\ \ g\in G \tag{24}$$

$$t_{i,g} \leq \text{OutT}_{i,g} + \text{MaxGateHold}_{i,g},\quad \forall i \in D,\ \ g\in G \tag{25}$$

$$t_{i,r} = \text{OnT}_{i,r},\quad \forall i \in A,\ \ r\in R \tag{26}$$

$$t_{i,u} = \text{FrozenT}_{i,u},\quad \forall i \in D'\bigcup A',\ \ u\in N \tag{27}$$

Similarly to Eqs. (1)-(8), D and A are the denotations for a set of departures and arrivals, respectively. N denotes a set of nodes on the taxiways, and I is for a set of intersection nodes, which is a subset of N. Similar denotations, R, G, and E, respectively represent a set of runway nodes, a set of gate nodes, and a set of links connecting two nodes in N. Decision variables are $t_{i,u}$, the passage time of aircraft i at node u along its taxi route, and z_{ij}^u which represents the relative order of passage at node u between aircraft i and j. In the cost function of Eq. (13), $\text{DesiredOff T}_{i,r}$ is the desired take-off time of aircraft i, and assumed to be given as target take-off times, which are the outputs of the runway scheduling problem in Section III. The first component of the cost function is to minimize late take-off times,

and the remaining components aim to minimize total taxi-out time for departures and total taxi-in time for arrivals, respectively. α_p, α_d, and α_a are the coefficients for weighting each cost component. According to Eq. (15), $t_{i,u}$ should have a positive real value. If aircraft *i* travels along the link (*u*,*v*), $t_{i,u}$ and $t_{i,v}$ should satisfy Eq. (17), where $\mathrm{MinTaxiT}_{uv}$ is the minimum travel time in link (*u*,*v*) determined by the maximum movement speed of aircraft *i* and the length of link (*u*,*v*), l_{uv}. Overtaking between aircraft *i* and *j* in the same link (*u*,*v*) is prevented by Eq. (18). Eq. (19) is for conflict resolution in bi-directional link (*u*,*v*). In Eqs. (20) and (21), Dsep_{ij} denotes the minimum required distance separation between aircraft *i* and *j*, and Eqs. (20) and (21) make it possible to maintain the minimum required separation between aircraft at the intersections. Eq. (22) is for runway separation, and the earliest possible take-off time constraint of Eq. (23) is also applied similarly to the runway scheduling. In Eqs. (24) and (25), $\mathrm{OutT}_{i,g}$ represents the earliest possible gate out time (pushback ready time) of aircraft *i*, and $\mathrm{MaxGateHold}_{i,g}$ is the maximum gate holding time limit to prevent a very late off-block time. In Eq. (26), $\mathrm{OnT}_{i,r}$ is the estimated landing times of arrival aircraft *i*, and assumed to be given and fixed. Eq. (27) is for frozen schedules of aircraft *i*, for the rolling horizon approach[3].

If we let C_{dep} be the set of crossing flights on RWY 33R/15L, C_{dep} is the subset of the set of departures, *D*, and the relative order of runway use among all flights in C_{dep} and arrivals in the set *A* should be determined. These runway crossings by departures on the arrival runway were not incorporated into the runway scheduling since there is no required separation between these runway crossings and take-offs. However, these runway crossings may cause taxi-time extensions, which should be taken into account in determination of optimal push-back times of those crossing flights. The additional constraints for these runway crossing operations in the taxi scheduling were formulated as Eqs. (28)-(31), where *R* denotes the set of departure runways, so that z_{ij}^{r} is the relative order of runway use between aircraft *i* and *j*, and $t_{j,r}$ is the runway usage time of aircraft *j*.

$$z_{ij}^{c} = z_{ij}^{r} \quad \forall i, j \in C_{dep},\ i \neq j,\ \ r \in R \tag{28}$$

$$t_{j,r} - t_{i,c} - \mathrm{Rsep}_{ij} \geq -M\left(1 - z_{ij}^{crs}\right), \quad \forall (i, j) \in (C_{dep} \times A) \tag{29}$$

$$t_{i,c} - t_{j,r} - \mathrm{Rsep}_{ji} \geq -M \cdot z_{ij}^{crs}, \quad \forall (i, j) \in (C_{dep} \times A) \tag{30}$$

$$z_{ij}^{crs} \in \{0, 1\}, \quad \forall (i, j) \in (C_{dep} \times A) \tag{31}$$

There is only one runway crossing point for the departures, and the taxi route from the crossing point to the runway queue is a single path. Therefore, the relative order of runway crossings should be the same as the relative order of departures as expressed in Eq. (28), where *c* denotes the runway crossing point. The binary variable z_{ij}^{crs} is for $\forall (i, j) \in (C_{dep} \times A)$ to denote the relative order of runway use between crossing flight *i* and arrival flight *j*, and the required separations between aircraft *i* and *j* are Rsep_{ij} when runway crossing of aircraft *i* occurs before landing of aircraft *j*, and Rsep_{ji} when arrival *j* is before crossing flight *i*. Runway crossings by arrival flights on RWY 33L/15R are also incorporated for taxi-in scheduling using similar constraints to Eqs. (28)-(31).

V. Optimization Tests

The proposed optimization models described in the previous sections for runway and taxiway scheduling of ICN surface operations were tested using a single scenario generated based on the operational data, in which the departure traffic volumes during 09:00-10:00 AM (one of the peak traffic hours) are assumed to be increased by 30%, compared to the normal departure traffic volume in April 2015.[2] Other traffic attributes, such as fleet mixture ratio for passenger vs. cargo flights, wake turbulence categories, and ratio of assigned runways and departure directions remain the same as in the operation data of ICN during the time. In addition to this single scenario test, a Monte-Carlo-based test is presented in order to look into computational tractability and cost performance of the proposed MILP-based model for the multiple runway scheduling problem for ICN. In the Monte-Carlo-based test, three different methods were applied for comparison of computation performances and the costs. Using the First-Come, First-Served (FCFS) solution as a baseline, the performance between the 'sequential optimization' and 'simultaneous optimization' was compared. For the FCFS solution, the fixed sequence based on the first-come, first-

served discipline was applied in the runway scheduling, where the runway usage sequence of the runway crossing flights and the departure flights without EDCT/CFR restriction was determined by the earliest possible runway usage times. The simultaneous optimization refers to solving a single optimization problem, where all of the flights on both runways are taken into account as shown in Fig. 3. In the sequential optimization, two independent optimization problems are solved sequentially as depicted in Fig. 4, where the required separation on the shared departure fix of the second optimization problem can be satisfied using Eqs. (6), (9), and (10)-(12). Fig. 3 and 4 show the scheduling steps of the two approaches. In the simultaneous optimization, the target take-off times on both RWY 33/15 and RWY 34/16 were calculated at the same time in one optimization search space. In the sequential optimization method, the runway scheduling for RWY 33/15 was computed first. Then, the multiple take-off time windows in Eq. (9) were calculated for departures from RWY 34/16 to the shared departure fix based on the calculated arrival times of the departures from RWY 33L/15R to the fix. Since the number of departures from RWY 33L/15R to the shared fix is smaller than the number of departures from RWY 34/16, it requires less take-off time windows and the assignment variables, s_i^k .

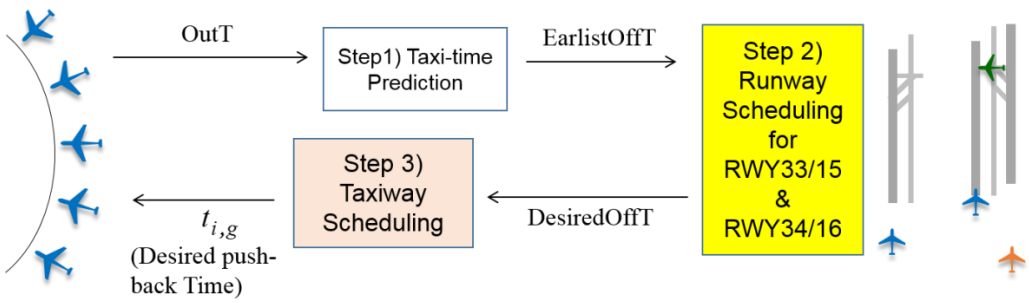

Figure 3. Scheduling architecture of surface traffic optimization in ICN using the simultaneous optimization for runway scheduling

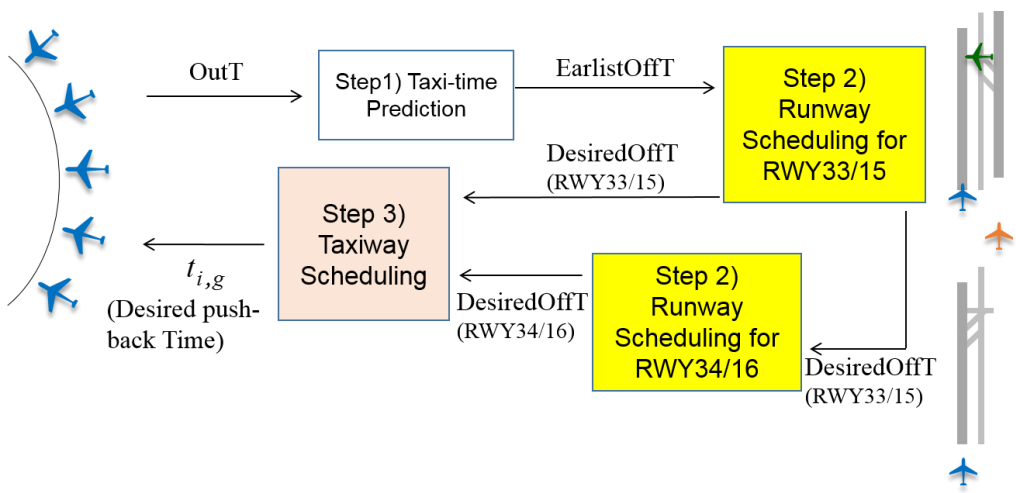

Figure 4. Scheduling architecture of surface traffic optimization in ICN using the sequential optimization for runway scheduling

A. Single Scenario Test

In this test scenario, 12 arrivals and 48 departures are included. Among the 12 arrivals of the scenario, 9 arrivals are passenger planes that need runway crossings, whereas the other 3 arrivals are freighters. For runway separation criteria, four wake turbulence categories, L (Light), M (Medium), H (Heavy), and SH (Super Heavy), are used. There are 19 departures that take off from RWY 33L/15R, and four of them should merge at the shared departure fix with the departures from RWY 34/16 on the south-bound route.

Table 1. Test scenario

Number of flights		Wake turbulence categories				Departure directions			
		L	M	H	SH	W-bound	S-bound	SE-bound	E-bound
12 Arrivals	12 on RWY 33R/15L	0	3	9	0	-	-	-	-
48 Departures	19 on RWY 33L/15R	0	5	13	1	0	4	8	7
	29 on RWY 34/16	0	13	16	0	18	11	0	0

Table 2 shows the runway separation rule between consecutive departures, and Table 3 presents the runway occupancy times of departure, arrival, and crossing aircraft in ICN. Required separations between an arrival and a departure or between a departure and a crossing aircraft are assumed to be the same as the runway occupancy time of the preceding aircraft plus 10 seconds.

Table 2. Runway separation between departures (sec)

		Trailing aircraft			
		L	M	H	SH
Leading aircraft	L	120	120	120	120
	M	180	120	120	120
	H	180	180	120	120
	SH	180	180	120	120

Table 3. Runway occupancy times (sec)

	L	M	H	SH
Arrival	80	52	45	45
Departure	85	57	50	50
Crossing	30	30	30	30

In the runway scheduling problem, a Constrained Position Shifting (CPS) constraint[3] in comparison with the take-off sequence of the FCFS solution was applied with the maximum position shift of 3, and a 15NM MIT constraint was imposed on departure fixes on both west and south-bound routes. The 15NM is an assumed value, and not from real flight data analysis.

The runway schedule optimization results are shown in Fig. 5. The calculated Target Take-Off Times (TTOTs) of all departures are shown on the bottom level of x-axis. The calculated take-off time and arrival time at the departure fix of each departure aircraft in the scenario are shown separately according to the departure directions. For comparison, the upper graph in Fig. 5 shows the optimization result without applying the MIT constraints. It is observed that some of the separations between the departures at the departure fixes on the west and south-bound routes are less than 15NM, whereas at least 15NM separations are maintained with applying the MIT constraints as shown in the lower graph. Both optimizations with and without MIT constraints in Fig. 5 were conducted by sequential scheduling, which optimized the flights on RWY 33/15 first and then optimized the schedule of departure flights on RWY 34/16 with multiple take-off time windows constraints imposed on the south-bound departures from RWY 34/16.

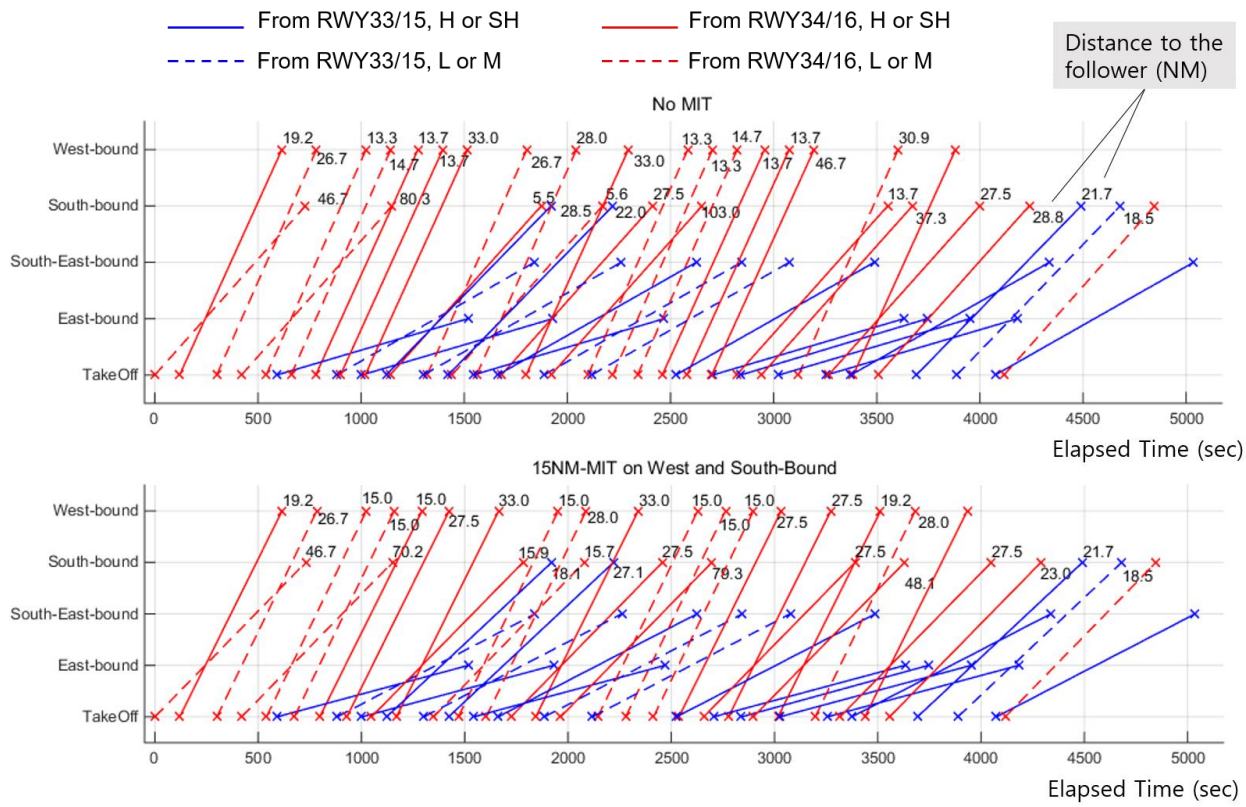

Figure 3. Passage times and separations at departure fixes (optimization results of the test scenario in Table 1)

For taxi scheduling, the required separation between a crossing flight and an arrival taxiing-in was set as the runway occupancy time of the preceding aircraft plus 10 seconds. In addition to minimizing the sum of late take-off times in the cost optimization, one more constraint was imposed in the taxi scheduling. This added constraint maintains the departure sequences of each runway in order to make the taxi scheduling results comply with the desired take-off times and sequences in the runway scheduling results as much as possible. Fig. 6 illustrates the proposed MILP optimal taxi scheduling results in comparison with FCFS scheduling. 'NoGH' denotes the case where no gate holding is allowed, in which only runway scheduling was applied. 'GH' denotes the case where taxi scheduling was applied to obtain the optimal pushback times. 'FCFS' means that the runway usage sequence was determined based on the first-come, first-served discipline with respect to the earliest possible runway usage times, whereas 'RWYSch' refer to the optimal runway sequencing and scheduling using the proposed MILP model conducted for departures. The preliminary results show that most of the taxi delays can be translated to holding times at gates by taxi scheduling, providing an opportunity for fuel savings on the surface movement area.

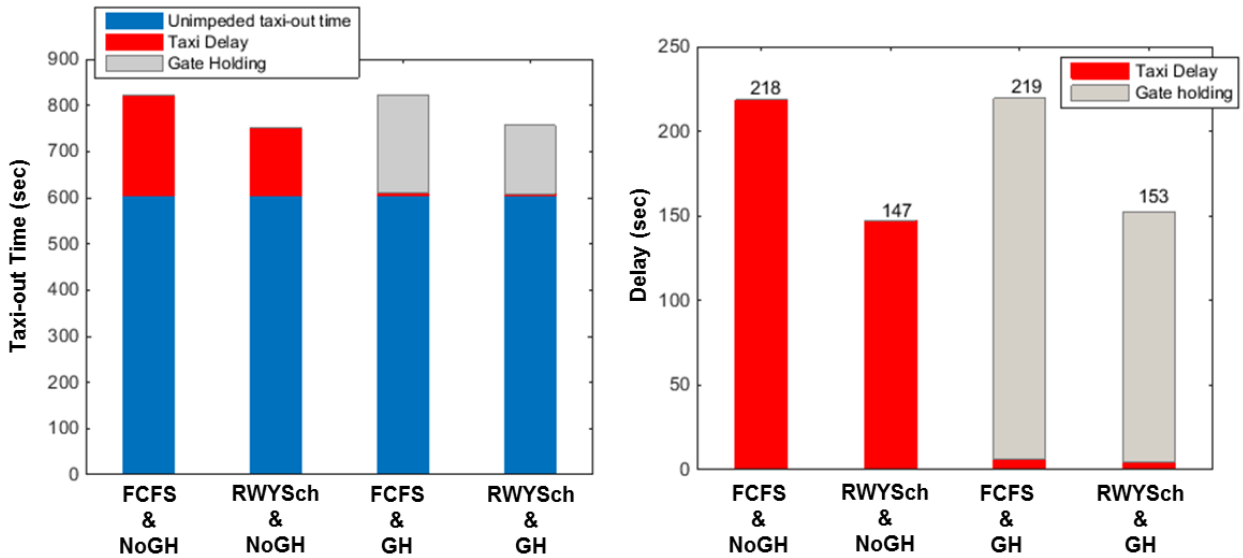

Figure 6. Averaged taxi-out time and delay per departure aircraft

B. Monte-Carlo Test for Runway Scheduling

The decision support tool for departure and surface management of ICN, currently being developed based on this study, requires a schedule for all departure aircraft for multiple runways in a planning horizon of 40-60 minutes, as described in Section II. Hence, there is a concern that the problem size might be large and require significant computational time. To investigate this, a Monte-Carlo test using 100 random scenarios for each test case was conducted.

Only one shared departure fix with 15-NM MIT separation constraint was used in this test. The test cases are given as follows. The total number of arrivals and departures in all scenario cases are the same, i.e., 40 departures and 20 arrivals for one hour. Only the number of departures from each runway to the shared departure fix is different, as depicted in Table 4. All other conditions, such as the number of runway crossings by arrival passenger planes, fleet mixture ratio for wake turbulence categories, and departure route directions, remain the same. The variation of test cases is based on the assumption that runway assignment strategy can put all the west and south bound departures to RWY 34/16.

Table 4. Differences of Test Cases

	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)

Fig. 7 shows the comparison of the computation times among the six test cases. The computation times on the y-axis are presented in a log scale, and each diamond marker denotes the average value of computation times of 100 different scenarios while the whiskers represent the 10th and 90th percentile. The largest value of the 90th percentile in the graph is about 310 seconds from the simultaneous optimization in case 2, while all 90th percentile values of the sequential optimization are less than 10 seconds. The simultaneous optimization shows remarkably long computation times compared to the sequential optimization. Another observation for the computation times of the simultaneous optimization is that the computation time decreases as the number of the departures from RWY 33L/15R to the shared departure fix with the MIT separation decreases from 5 (Case 0) to 0 (Case 5), despite of the

same problem sizes over Case 0 to 5. This shows the computational difficulty in finding an optimal sequence of the runway scheduling problem with a MIT separation between the departures from different runways. Contrary to the computation times of the simultaneous optimization, that of the sequential optimization is increasing as the number of departures from RWY 34/16 increases from 25 (Case 0) to 30 (Case 5). At the same time, the number of take-off time windows, N_{W_i} in Eq. (9), decreases from 6 to 1 in runway scheduling for RWY 34/16. Although the optimization problem size is dependent on the number of take-off time windows, the number of flights in the optimization model appears to have more impact on the computation time. All optimizations were solved by using CPLEX on a desktop computer with Intel i7-6820HQ @2.70GHz and 32GB RAM.

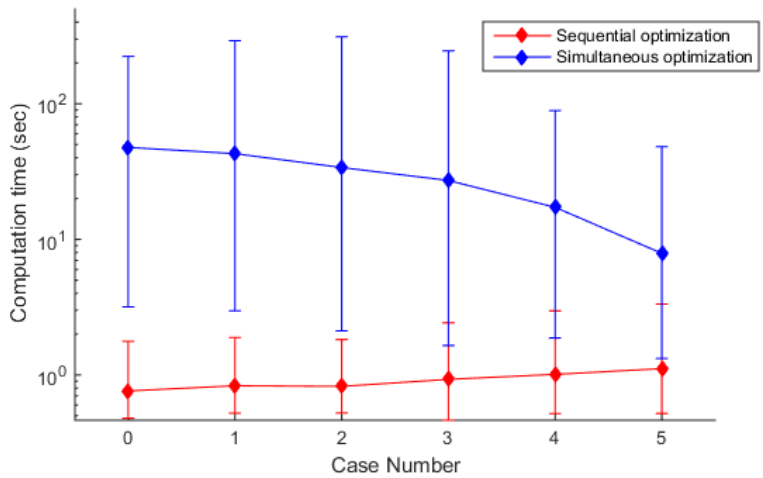

Figure 4. Computation time comparison in log scale.

The scheduling costs by the three methods are compared in Fig. 8, where each asterisk denotes the average value of the costs from a 100 different scenarios for each test case. It is obvious that the simultaneous optimization can provide the best solution, but in Fig. 8, it is also shown that the sequential optimization provides reasonably good costs compared to the FCFS solutions. In the cost improvements over the FCFS solution shown in Fig. 9, as the number of departures from RWY 33L/15R decreases, the cost improvements of sequential optimization and simultaneous optimization converge. The averaged improvements of the simultaneous optimization and the sequential optimization are 20.98% and 15.86%, respectively.

According to the test results shown in Figs. 7-9, the best solution can be obtained by the simultaneous optimization, but the computation time increases due to the large problem size. In terms of the computation time performance, sequential optimization shows much better performance with reasonably low cost.

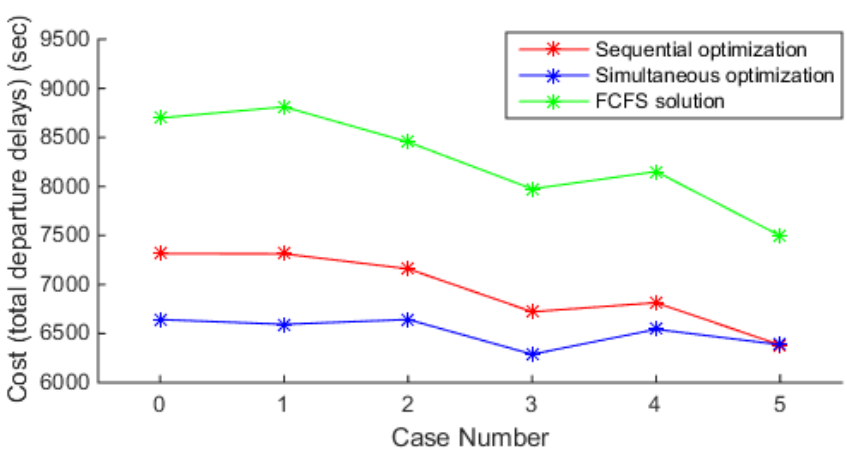

Figure 8. Optimization cost comparison.

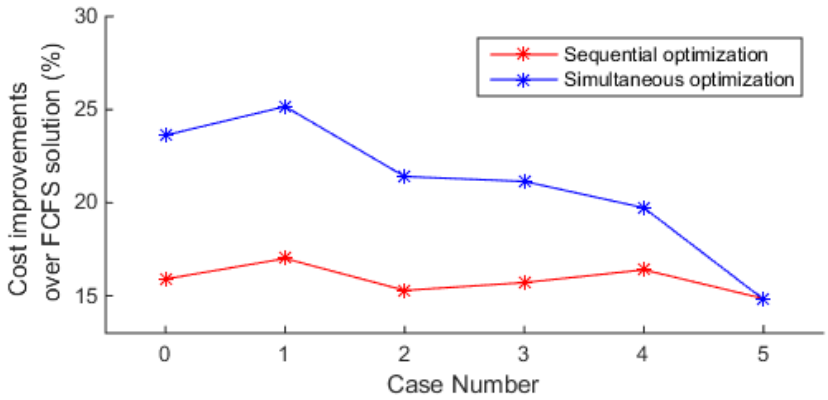

Figure 9. Cost improvements over FCFS solution.

VI. Conclusion

A surface traffic optimization model was studied as a preliminary step in developing a controller decision support tool for integrating departure and surface management at ICN. MILP-based optimization models for runway scheduling and taxiway scheduling of ICN were developed. In the development of the optimization models, various types of TMIs including 'multiple take-off time windows,' which is specific for ICN, as well as MIT, CFR, and EDCT were incorporated. Two different types of runway crossings on the coupled runways 33L/15R and 33R/15L - departure runway crossings by arrival passenger planes and arrival runway crossings by departure freighters - were separated and incorporated into the runway scheduling and taxiway scheduling problems, respectively. Based on the identified operational characteristics of ICN[2], multiple runway scheduling methods with consideration of MIT separation at the shared departure fixes from both departure runways, RWY 33L/15R and 34/16, were investigated. The sequential optimization approach using 'multiple take-off time windows' constraints was proposed for reasonable scheduling performance and less computation intensity. If high performance computation resource is available, the simultaneous optimization for multiple runway scheduling approach would be desirable, but large deviations of computation times found in the Monte-Carlo test results should also be taken into account. Overall, the sequential optimization would be a balanced implementation for an automated decision support tool. The 'multiple take-off time windows' concept and the sequential optimization approach might be practically useful to schedule take-off times of departures for an airport with multiple runways, as well as for multiple airports in a metroplex environment.

In future studies, additional requirements from ANSP (Air Navigation Service Provider) of ICN, such as cruise altitude assignment to the departure flights with consideration of separation requirements, will be considered. In addition, a runway assignment problem for runway balancing at an airport with multiple departure runways can be integrated in the scheduling model.

Acknowledgments

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References

[1]EUROCONTROL, "The Manual: Airport CDM Implementation," v. 4, Brussels, Belgium, 2012.

[2]Eun, Y., Jeon, D., Lee, H., Zhu, Z., Jung, Y.C., Jeong, M., Kim, H., Oh, E., Hong, S., Lee, J., "Operational Characteristics Identification and Simulation Model Validation for Incheon International Airport," *the 16th AIAA Aviation Technology, Integration and Operations Conference*, Washington, DC, June 2016.

[3]Lee, H., "Airport Surface Traffic Optimization and Simulation in the Presence of Uncertainties," Ph.D. Dissertation, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2014.

[4]Lee, H., and Balakrishnan, H., "A Comparison of Two Optimization Approaches for Airport Taxiway and Runway Scheduling," *the 31st Digital Avionics Systems Conference*, Williamsburg, VA, October 2012.

[5]Clare, G.L., Richard, A.G., "Optimization of Taxiway Routing and Runway Scheduling," *IEEE Transactions on Intelligent Transportation Systems*, Vol. 12, No. 4, 2011, pp. 1000-1013.

[6]Koeners, G.J.M., Stout, E.P., Rademaker, R.M., "Improving Taxi Traffic Flow by Real-Time Runway Sequence Optimization using Dynamic Taxi Route Planning," *the 30th Digital Avionics Systems Conference*, Seattle, WA, October 2011.

[7]Deau, R., Gotteland, J.B., and Durand, N., "Runways Sequences and Ground Traffic Optimization," Proceedings of the 3rd International conference on Research in Air Transportation, Fairfax, VA, June 2008.

[8]Gupta, G., and Malik, W., "A Mixed Integer Linear Programming for Airport Departure Scheduling," the 9th AIAA Aviation Technology, Integration, and Operations Conference, Hilton Head, SC, September 2009.

[9]Rathinam, S., Wood, Z., Sridhar, B., and Jung, Y.C., "A Generalized Dynamic Programming approach for a departure scheduling problem," *AIAA Guidance, Navigation, and Control Conference*, Chicago, IL, August 2009.

[10]Malik, A.M., Lee, H., Jung, Y.C., "Runway Scheduling for Charlotte Douglas International Airport," *the 16ht AIAA Aviation Technology, Integration and Operations Conference*, Washington, DC, June 2016.

[11]Malik, A.M., and Jung, Y.C., "Exact and Heuristic Algorithms for Runway Scheduling," *the 16ht AIAA Aviation Technology, Integration and Operations Conference*, Washington, DC, June 2016.

[12]Balakrishnan, H., and Jung, Y., "A Framework for Coordinated Surface Operations Planning at Dallas-Fort Worth International Airport," *AIAA Guidance, Navigation and Control Conference and Exhibit*, Hilton Head, SC, August 2007.

[13]Frankovich, M. J., "Air Traffic Flow Management at Airports: a Unified Optimization Approach," Ph.D. Dissertation, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2012.

[14]Smeltink, J.W., Sommer, M.J., Waal, P.R, and Van der Mei, R.D., "An Optimization Model for Airport Taxi Scheduling," NLR-TP-2003-475, 2003.

[15]Pesic, B., Durand, N., and Aliot, J.M., "*Aircraft Ground Traffic Optimization Optimisation Using a Genetic algorithm," In Proceedings of the Genetic and Evolutionary computation Conference*, San Francisco, CA, 2001.

[16]Liu, C., and Guo, K., "Airport Taxi Scheduling Optimization Based on Genetic Algorithm," *International conference on Computational Intelligence and Security*, Nanning, Guangxi, China, December 2010.

[17]Adacher, L., and Flamini, M., "Aircraft Ground Routing and Scheduling Optimization," the 2014 *UKSim-AMSS 16th International Conference on Computer Modelling and Simulation*, Cambridge, United Kingdom, March 2014.

[18] Tsao, H.S., Wei, W., Pratama, A., and Yang, S., "Integrated Taxiing and Take-Off Scheduling for Optimization of Airport surface Operations," the 2nd International Conference on Decision Sciences in Global enterprise Management, Bombay, India, January 2009,

[19] Yu, C., Lau, H.Y.K., "Integrated Optimization of Airport Taxiway and Runway Scheduling,*" Journal of Automation and Control Engineering*, Vol. 2, No. 4, pp. 338-342, 2014.

[20]Montoya, J., Rathinam, S., and Wood, Zachary, "Multiobjective Departure Runway Scheduling Using Dynamic Programming," IEEE Transactions on Intelligent Transportation Systems," Vol. 15, No. 1, pp. 399-413, 2014.

[21]Lee, H., Simaiakis, I., and Balakrishnan, H., "A comparison of Aircraft Trajectory-based And Aggregate Queue-Based Control of Airport Taxi Processes," *the 29th Digital Avionics Systems Conference*, Salt Lake City, UT, October 2010.

[22] Chandran, B., Balakrishnan, H., "A Dynamic Programming Algorithm for Robust Runway Scheduling," *Proceedings of the 2007 American Control Conference*, New York, July 2007.

[23]Jung, Y.C., Hoang, T., and Montoya, J., "A Concept and Implementation of Optimized Operations of Airport Surface Traffic," the 10th AIAA Aviation Technology, Integration and Operations Conference, Fort Worth, TX, September 2010.

[24]Atkin, J.A.D., Burke, E.K., Greenwood, J.S., and Reeson, D., "A Metaheuristic Approach to Aircraft Departure Scheduling at London Heathrow Airport," 9th International Conference on Computer-Aided Scheduling of Public Transport, San Diego, CA, August 2004.