Real-Time Integrated Airport Surface Operations Management

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Abstract— This paper describes a real-time integrated airport surface operations management (RTI-ASOM) that provides optimal 4-D trajectories for each aircraft between the gate and runway with the objective of minimizing taxi delay and maximizing runway throughput. The use of Mixed Integer Linear Programming (MIP) formulation, Dynamic Programming for runway sequencing, and Visual Basic scripted interface allows an efficient solution algorithm that can solve the large-scale optimization problem instantly, with examples based on one-day track data at LaGuardia Airport (LGA). The results show that average taxi-out time of departure flight can be reduced by 83% and average taxi-in time of arrival flight can be reduced by 61%.

Keywords: Airport surface movement, threaded track data, departure and arrival sequencing, 4-D trajectory, Mixed-integer linear programming (MIP)

I. INTRODUCTION

A. Background

Demand for aviation will continue to grow steadily over the long run as the economy recovers from the impacts of the recent financial crisis. Since 1970's, air traffic has doubled every 15 years and is expected to double again in the next 15 years, with 4.7% world annual traffic growth in terms of RPK (Revenue Passenger Kilometers) (1). For the next 20 years, the 2013 FAA forecast calls for U.S. annual carrier passenger growth to average 2.2 % (2). For European air traffic growth, the forecasted annual growth rate is 3.7%, reaching 15.9M by 2030 from a base of 9.2M in 2005 (3). The anticipated growth of traffic demand will cause the current airspace system, which is already burdened, to become more congested, with increasing delay and consequential economic and environmental penalties.

Busy airports in the National Airspace System (NAS) are bottlenecks to the system. Delays and congestion at these airports have significant impacts on the performance of terminal airspace and en route sections, and will propagate to the entire NAS (4, 5). Thus, improving the efficiency of airport operation is essential for alleviating the congestion caused by increasing demand. One intuitive way to achieve this goal is to expand airport capacity by adding more runways and expanding taxiways and terminal areas. Nevertheless, such solutions are very expensive, especially for airports with limited physical space and under rigorous environmental regulations. In addition, airport expansion projects take many years to be approved and executed, while the situations at airports deteriorate further and impair the performance of the entire air traffic network. Therefore, it has become more and more important to improve airport operations by using existing facilities as efficiently as possible.

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B. Airport Surface Operations

Air traffic control at airport surfaces includes arrival and departure management of runways, routing of aircraft on taxiways, and gate allocation/release. Usually, the sequence of arrival flights is managed in an orderly manner within the terminal area. After landing on a runway, aircraft are directed to an allocated gate by following a designated taxiing route to avoid conflicts with other aircraft on the surface. Arrival flights tend to experience less holding time in practice because the delay cost per unit time of arrivals is much more than that of departures (6). Following the operational procedure of many airlines, departure flights do not turn on all engines while taxiing out, thus consuming less fuel per unit time than arriving flights. The management of the departure process is comparably more complex. After finishing the loading process and receiving clearance from the controller, the aircraft can start to push back from the gate. When entering into the active movement area, departure flights are directed through the taxiway system to the designated takeoff runway. During the taxi-out phase, flights might be assigned a certain amount of wait time at holding points to avoid potential conflicts with others or the flight priority may be adjusted. Varied by runway configuration and fleet mix, runway clearance is issued to the next aircraft i.e. aircraft waiting at the runway end or arrival aircraft around the terminal for landing, as soon as the runway is cleared for the next operation. Taxiways connect runways with the apron area where aircraft park to load passengers and baggage. To maintain safety operations on the airport surface, no conflict of any kind is allowed for any aircraft, such as head-on, trailing, or crossing conflicts in an active movement area. In addition, a set of spatial separation requirements is for any two successive aircraft moving on the same segment of a runway and taxiway to avoid the impact of wake vortex.

Ground delay and surface congestion impair operations at the airport surface and other areas of the air traffic system. Such delays deteriorate the punctuality of flights at the destination airport and add uncertainty and unpredictability to connecting flights. It also can contribute to inefficient use of scarce facilities resources, as well as excessive fuel burn and emissions. As a result, delays and congestion add to the direct operational cost of airports and airlines, increase passenger dissatisfaction and inconvenience, and cause environmental penalties for the local community. An increase of about 21% on average taxi-out time was reported from 1995 to 2007 in the U.S. (7-9). The excess fuel burned during taxiing in the U.S is about 75kg per flight, accounting for 26% of fuel savings among the estimated benefit pool actionable by Air Navigation Service (10). To address the inefficiency of surface operation, several concepts and procedures have been tested at some U.S. airports, mostly involving departure queue management that aims at shifting the excessive taxiing time to the gate. The methods include Collaborative Departure Queue Management (CDMQ) (11), pushback rate control (12), and virtual queue departure management (11). Spot and Runway Departure Advisor, developed by NASA (SARDA) (13), and Tower Flight Data Manager (TFDM), initiated by FAA (14), endeavor to offer terminal automation platforms to support decision-making in airport surface operations. Specifically, SARDA provides advisories on sequence and timing for releasing departures at the spot and runway using Dynamic Programming formulation, with the objective of maximizing runway throughput (13). TFDM provides taxi route advisories, monitors taxi route conformance, and alerts controllers of deviations of aircraft from an assigned route or any conflict between aircraft and ground vehicles (16). The outcomes of these tools are promising in terms of reducing taxiing times, fuel burn, and associated emissions, but they have primarily focused on queue management at one airside facility at a time, and the estimated delay reduction is shown with discrete flight data at the study airports (17-20). No studies have tackled integrated operations management involving all airport airside facilities simultaneously.

As an evolution of Air Traffic Control (ATC) in the U.S., NextGen aims to improve ATM performance by transforming the current surveillance-based control to trajectory-based control (11). For airport stakeholders, trajectory based operations (TBO) will provide new capabilities to improve safety and accessibility at airports and also will enable aircraft to fly negotiated flight paths by taking both operator preferences and optimal system performance into consideration. Even though certain challenges exist, such as sufficient surveillance coverage at service area, 4-D TBO identifies the future trend of ATC.

C. Research Objective

To fill the gap in existing literature and embrace the trajectory-based control of NextGen, a real-time integrated airport surface operations management (RTI-ASOM) is proposed in this study. Integrated management means that for both arrivals and departures, holistic control strategies will be developed to manage all flight operations between gate and runway (including the sequencing of landing and takeoff). Real-time means that the proposed strategy is based on real-time inputs from the cockpit and the control tower, and decision support to controllers and pilots also are made in real-time. The objective of RTI-ASOM is to increase the efficiency of surface operations by (1) reducing taxiing delay and (2) improving runway throughput. It is modeled with mixed integer programming (MIP), and a solution algorithm is developed to solve the problem efficiently. The outcomes of the model include optimal passage time of aircraft going through each node in a digitalized airport network. Such information can be shared via a data link between the control tower and the Flight Management System in the cockpit (21) and create an automation platform that can enable the control of complicated surface operations in a safe and orderly manner.

The proposed integrated management entails several benefits. First, it improves airport operations by mitigating surface congestion and reducing excessive fuel consumption and consequent environmental impacts. Second, it augments the predictability of airport operations and enhances the management capability of the Central Flow Management Unit (CFMU), which will then lead to better system performance for the entire NAS. Third, it extends the 4-D trajectory concept from airspace to airport surface and makes gate-to-gate 4-D trajectory based air traffic management practicable.

The remainder of this paper is organized as follows. Current research is summarized in Section II. The problem definition of RTI-ASOM is described in Section III, followed by formulation of the problem in Section IV and discussion of the solution algorithm in Section V. A case study at LGA with detailed numerical analysis is presented in Sections VI and VII, followed by concluding remarks in Section VIII.

II. LITERATURE REVIEW

This section summarizes existing literature on airport surface operations management. Related research is categorized into three groups based on primary focus: 1) runway operations planning, including constrained position shifting (22); departure queue management (11, 18); and runway scheduling (13, 23); 2) taxi planning, including route allocation (24, 25), and taxiway scheduling (26, 27); and 3) gate allocation (28) and pushback control (12). SARDA manages surface operations with two separate but interacting schedulers (13). The Spot Release Planner provides an optimal schedule to release departures on the spot (the hand-off point on the surface between the ramp control and tower control) with the objective of maximizing runway throughput. The Runway Scheduler provides runway-crossing sequence for arrivals while maintaining optimal throughput. However, gate management or time control was not included in SARDA. In some studies (6, 25, 29), both taxiway planning and runway scheduling are considered over a small constructed scenario with limited practical features. In another study (30), more realistic features are considered with proposed local de-conflicting algorithm. However, the algorithm is not efficient enough to solve the problem within instant time for real-time controlling purposes. In contrast, this paper combines gate pushback controlling, taxiway scheduling, and runway sequencing together and proposes an efficient decomposition algorithm to solve the optimization model. Realistic features on surface operation control are included in the model, and an automated tool with a user-friendly interface also was developed to facilitate real-time management.

From the methodology aspect, methods used in related research to formulate airport surface operation problem can be classified as follows: 1) Mixed Integer Linear Programming (MIP) (23, 25, 26, 27, 30), 2) Genetic Algorithm (GA) (15, 28), and 3) Dynamic Programming (6, 13). MIP is used widely to formulate taxiway planning problems (25, 26, 27, 30) to minimize taxiing time and runway scheduling problem (23) to maximize runway throughput. With piecewise linear objective and constraints, it can be used to solve optimization problems using special ordered sets. For real-time planning purpose, computational efficiency is one of the main challenges using MIP, and various pre-processing methods have been developed to speed up the computation (25, 26, 30). Genetic Algorithm (GA) often is used to search a theoretical solution for gate assignment problems (28) or taxiway scheduling problems (15). It is a search heuristic that repeatedly generates, modifies, and selects from a population of randomly-generated solutions until the best one is found or terminated due to pre-determined rules. Examples are usually conducted at constructed airports with simulated (15) or realistic flight data (28). Dynamic Programming (DP) is numerically feasible only for special classes of (typically discrete) problems and, therefore, is often used to solve the optimization problem of flight sequencing (6, 13). It is a general recursive decomposition technique for optimization problems. When the problem structure is favorable, such as runway sequencing problems (6, 13), DP can provide an optimal solution efficiently. In this study, the MIP method was adopted to formulate the integrated surface movement optimization problem, and DP is applied as part of decomposition algorithm to solve the problem efficiently.

III. PROBLEM DEFINITION

Given a set of departure and arrival flights, the model proposed in this study optimizes aircraft surface movement by balancing two objectives: 1) maximal runway usage and 2) minimal total taxiing times, subject to the operational constraints of recursive planning requirements, ready time limits, conflict-free constraints, precedence constraints, minimum separation requirements, and speed limits (discussed in details below). The outcomes of the optimization problem are optimal 4-D trajectories for aircraft between the gate and the end of runway.

A. Recursive Planning Horizon

For real-time planning purposes, the entire day is split into small time windows, such as every 5 minutes. The length of planning horizon could vary from airport to airport and also could depend on the operational conditions of the airport surface. Any aircraft that is ready-to-move will be either cleared within this planning horizon or postponed to following planning periods.

Aircraft are not only constrained to avoid conflict with others in the same window, but also are required to have spatial separation from aircraft scheduled in previous windows that are still remaining on the surface. To achieve this, the status of each node in the airport surface network is updated with the latest passage time from the previous planning period. Such information is then converted as a set of new constraints for the consecutive planning period.

B. Ready time limit

The ready time of a departure aircraft is the target off-block time (TOBT), i.e., the time that the aircraft operator estimates that an aircraft is ready (all doors closed, boarding bridge removed, a pushback vehicle present) to push back immediately upon reception of clearance from the tower. The ready time of an arrival flight is the estimated time of arrival (ETA), i.e. the earliest time estimated at the beginning of the planning horizon when an aircraft would reach the runway, if there was no interference from other aircraft (34). Ready times of arrivals and departures are the inputs of the model and are shown in the constraints so that no flight will push back or land before the ready time.

C. CONFLICT-FREE CONSTRAINTS

For safety and efficiency purposes, the optimized 4-D trajectory should be conflict-free. There are three types of conflicts: crossing conflict, trailing conflict, and head-on conflict. The decision variable t_{iu} represents the time for aircraft *i* to pass node *u* in the network. A set of constraints is included in the model to make sure that no aircraft will cross, trail, or head-on towards another at the same node or segment in the network.

D. Precedence Constraint

Some airports have an extended surface area for reordering the sequence of aircraft before takeoff. However, reordering can elongate the taxiing times of aircraft. In this study, given a short planning horizon, aircraft reordering at the end of a runway is not considered. Instead, precedence constraint is included in the model to govern the right-of-way of aircraft, i.e., the runway sequence will be followed such that an earlier aircraft gets priority when going through the same node or segment in the network.

E. Minimum Separation Requirements

While waiting for clearance to access on a runway, aircraft are required to maintain certain separations to prevent the danger of wake turbulence. Minimum time separations between aircraft (see Table 1) differ for various leading and trailing aircraft types, which are based on the maximum takeoff weight (MTOW).

TABLE 1 Minimum time separation (in sec) between two successive arrival/departure aircraft on same runway (33)

Arrivals/ Departures	**Trailing Aircraft**		
Leading Aircraft	*Dep_Heavy*	*Dep_Medium*	*Dep_Light*
Dep_Heavy	96/90	157/120	196/120
Dep_Medium	60/60	69/60	131/60
Dep_Light	60/45	69/45	82/45

Note: ICAO wake turbulence category (WTC) (32):

- H (Heavy) aircraft types = 136 000 kg (300 000 lb) or more.
- M (Medium) aircraft types = less than 136 000 kg (300 000 lb) and more than 7 000 kg (15 500 lb).
- L (Light) aircraft types = 7 000 kg (15 500 lb) or less.

In addition, when an airport has two active runways intersecting with each other, a time separation of 55seconds is required to advance aircraft to another runway.

Also in the taxiway area, a separation distance sep_T is required to avoid conflicts and maintain safety. A separation distance sep_T=200 meter (26) complies with all safety regulations on the taxiway.

F. Speed Limit

To maintain safety operations on the airport surface, the movements of aircraft are constrained by a maximum taxing speed. The optimized aircraft surface movement should be compliant with the possible taxiing speed ranges of an aircraft. For this purpose, constraints are derived to set the minimum time needed for each flight traversing each segment.

IV. MATHEMATICAL FORMULATION

In general, the network for airport surface movement can be represented by a directed graph *G=(V, E)*, with V being the set of nodes representing intersections on taxiway/runways and E being the set of directed links representing taxiway segments between two intersections. The nomenclature of the index sets and inputs are listed as follows:

A	Set of arrival flights
D	Set of departure flights
N	Set of all nodes
RN	Set of runway nodes, RN∈*N*
TN	Set of taxiway nodes, TN∈*N*, $\text{RN} \cup \text{TN} = N$
T_i	Earliest ready time of aircraft *i*
S_T	Minimum separation distance between any two aircraft on taxiway
S_R	Minimum separation matrix when using same runway
L_{uv}	Link distance between adjacent node *u* & *v*
T_u	Last passage time of node u

To mitigate congestion on the airport surface and maximize the use of limited airside facilities, the objective of this model is to minimize the total taxiing time of all aircraft and maximize runway throughput. Let t_{iu_1} denote the time of aircraft *i* to visit its first node u_1 (gate for departure flights and runway for arrival flights), t_{iu_k} the time of aircraft *i* to visit its last node u_k on the surface (end of runway for departure flights and gate for arrival flights), and $t_{i'u'_k}$ the time of last aircraft i' in the planning horizon to visit its last node u'_k along its route. Then, the total taxiing time for aircraft i considered in a planning horizon is $\sum_i(t_{iu_k} - t_{iu_1})$. The $t_{i'u'_k}$ can be used to represent the runway throughput; a smaller value yields greater runway throughput. By modeling in this way, multiple objectives can be combined into one minimization function. In addition, a weight factor W is introduced in the objective function to balance the performance of different components of the airport surface and is subject to change based on airport operator judgment. For instance, if extensive runway queues but moderate surface traffic are observed at one airport, then for that airport, the weight in the objective function could be set lower to give primacy to runway utilization.

In addition to decision variables t_{iu_k}, a bianary variable z_{ij} is introduced to determine the sequence of any two aircraft when using the same link along their routes. Variable $z_{ij} = 1$ if aircraft i visit any common node u before aircraft j and 0, otherwise:

$$z_{ij} = \begin{cases} 1, \text{if } t_{iu} < t_{ju} \\ 0, \text{o/w} \end{cases}$$

The mathematical formulation of the proposed optimization problem is the following:

$$\text{Min } (1\text{-W}) * t_{i'u'_k} + \text{W} * \sum_i(t_{iu_k} - t_{iu_1})$$

s.t.

$$t_{iu} \geq T_i, \forall i \quad (1)$$
$$z_{ij} \times (t_{ju} - t_{iu}) \geq 0,\ \forall i,j,\ i \neq j \quad (2)$$
$$z_{ij} \times (t_{ju} - t_{iu} - \frac{S_T}{spd}) \geq 0, \forall u \in V_i \cap V_j \quad (3)$$
$$z_{ij} \times (t_{ju} - t_{iu} - S_R) \geq 0,\ \forall u \in RN,\ i \neq j \quad (4)$$
$$\frac{L_{uv}}{SPD_{max}} \leq t_{iv} - t_{iu}, \forall i, \forall (u,v) \epsilon E_i \quad (5)$$
$$t_{iu} - T_u \geq S_R, \forall u \in RN \quad (6)$$
$$t_{iu} - T_u \geq S_T, \forall u \in TN \quad (7)$$

Constraint 1 implies that any aircraft must not start to visit any node at an airport surface before its earliest ready time. Constraint 2 ensures that no potential conflict exists among all surface movement and also enforces the precedence constraint with binary variable z. Minimum separation requirements on the taxiway and runway are defined in Constraints 3 and 4, respectively. Constraint 5 imposes the speed limit for all active aircraft in the planning window. Constraints 6 and 7 ensure that each taxiway intersection and runway end passed by an active flight in the current planning window are cleared with certain separation from other flights in previous planning windows.

V. SOLUTION ALGORITHM

A. Linearization

Some constraints previously listed are in a nonlinear format. As a first step, the nonlinear equations (2, 3, 4) are reformulated for use in the MIP by introducing a large scalar M. The linearized formulation is as follows:

$$\text{Min } (1\text{-W}) * t_{i'u'_k} + \text{W} * \sum_i(t_{iu_k} - t_{iu_1})$$

s.t.

$$t_{iu} \geq T_i, \forall i \quad (1)$$
$$t_{iu} < t_{ju} + M \times (1 - z_{ij}),\ \forall i,j,\ \forall u \in V_i \cap V_j \quad (2a)$$
$$t_{iu} > t_{ju} - M \times z_{ij}, \forall i,j,\ \forall u \in V_i \cap V_j \quad (2b)$$
$$\frac{S_T}{spd} < t_{ju} - t_{iu} + M \times (1 - z_{ij}),\ \forall i,j, \forall u \in V_i \cap V_j \quad (3a)$$
$$\frac{S_T}{spd} > t_{ju} - t_{iu} - M \times z_{ij}, \forall i,j,\ \forall u \in V_i \cap V_j \quad (3b)$$
$$S_R < t_{ju} - t_{iu} + M \times (1 - z_{ij}),\ \forall i,j,\ \forall u \in V_i \cap V_j \quad (4a)$$
$$S_R > t_{ju} - t_{iu} - M \times z_{ij}, \forall i,j,\ \forall u \in V_i \cap V_j \quad (4b)$$

$$\frac{L_{uv}}{SPD_{max}} \le t_{iv} - t_{iu}, \forall i, \forall (u,v) \epsilon E_i \quad (5)$$

$$t_{iu} - T_u \ge S_R, \forall u \in RN \quad (6)$$

$$t_{iu} - T_u \ge S_T, \forall u \in TN \quad (7)$$

B. Decomposition Algorithm

To solve the above MIP problem, a decomposition algorithm is introduced to obtain the optimal solution efficiently.

The main idea behind this decomposition algorithm is to narrow the feasible area of sequence binary variable z(i,j) so that the complexity of the optimization model is reduced to an executable level for commercial solvers. In the first stage, dynamic programming is applied to determine a number of sequence options that are highly likely to be the optimal runway sequence for both departure and arrival flights. Each sequence option is converted into a set of binary variable z(i,j). In the second stage, given z(i,j) as known, the MIP is solved, and decision variables t_{iu} are obtained. After running through all sequence options, the values of objective functions are compared, and the optimal trajectory-based timing solution is selected as the one with the minimal value.

C. Dynamic Programming for Runway Sequencing

The idea of applying dynamic programming is to determine highly-likely optimal runway sequences to reduce the feasible region of the model and reduce the model complexity.

Given the number of flights to be scheduled in each planning horizon, the TOBT and estimated taxiing time for departures, and the ETA for arrivals, dynamic programming recursion is conducted to search through all possible options of runway sequences, and those with high runway throughput estimates are exported for use in the next stage. Let T(j) be the earliest ready time of flight j, T(s,j) the earliest runway access time for flight j at stage s, and T'(s,j) the estimate of T(s,j). T'(s,j) is derived from predecessor flight T(s-1, i) to ensure certain separation requirement sep(i,j).

For each two successive flights (i, j) occupying the runway, T(s,j) must be greater than earliest ready time T(j) and estimated runway access time from the previous flight T'(s,j). The pseudo code is shown as follows:

```
For each stage s=1,...n
    For each flight j in stage s
        For each predecessor flight i of flight j
            T'(s,j) = min T(s-1,i) +sep(i,j) among all predecessors;
            pred(s,j)=i with the min T'(s,j);
        End
    T(s,j) = max(T(j)+UnimpedTaxiTime(j), T'(s,j));
    End
End
LastT=min T(s,j) among all j when s=n;
LastFlight=arg min T(s,j).
```

Each sequence option with high estimated runway throughput is represented by a matrix of binary variable z(i,j). It is assumed that the sequence will be kept along the planning horizon, and no overtaking or sequence reordering is allowed once the sequence is given. For each given sequence option, the mathematical model is solved with CPLEX. Finally, the solution with the minimal objective function value (weighted function of taxi delay and runway throughput) is selected after running through all potential sequence options.

D. User Interface

Dynamic Programming for flight sequences is translated into Visual Basic (VB) language, and the optimization model is programmed in General Algebraic Modeling System (GAMS) and solved using CPLEX. A GAMS model file contains the constraint forms and objective function for all instances, whereas the data are read from and written to an Excel file. The entire programming process is integrated and automated using a series of VB scripts. Multiple modules are built consecutively, and a user interface is constructed, as shown in Figure 1. Each module calls for and executes each piece of VB script. After executing listed modules by sequence, the problem solution is presented in the same file with optimized 4-D trajectory for all the active flights in the planning window.

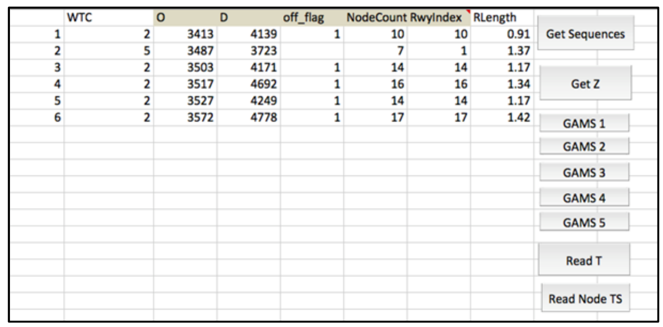

Figure 1 Snapshot of VBA Modules and Example of Model Input

VI. CASE STUDY

To demonstrate the operability of the MIP formulation with a solution algorithm and illustrate the benefit of the proposed RTI-ASOM, a case study was constructed using the LaGuardia Airport (LGA) layout and surface track data.

LGA is one of three major commercial airports in the New York region, with two runways that intersect each other. In practice, most of departure flights are assigned to take off on runway 4-22 and arrival flights land on runway 31-13 (see Figure 2). For the case study, we first digitalized the airport surface into a node-link network. LGA's layout is represented by the 66-node graph structure shown in Figure 2. The airside facilities identified in the graph include terminal gates, taxiway intersections, and runway ends. Taxiway and runway segments are denoted by directed links connecting each two adjacent nodes.

One-day surface track data on December 14, 2010 were used for the case study. The surface data includes radar track data recorded within the terminal and flight tracks from individual sensors. The two resources were joined together to create a unified trajectory for each flight at the airport (consecutive green dots in Figure 2).

Figure 2 LGA surface networks with nodes and links

The surface track data provides historical 4-D trajectories of flight operations at airport surface. However, not all the inputs needed for the modeling are available from the track data. For example, the data contain neither the TOBT nor the ETA. However, conversations with tower controllers indicated that, in current operations, they usually do not hinder the pushback of the aircraft. Thus, the historical pushback time could be considered as the TOBT. In addition, it was assumed the actual landing time is the ETA of an aircraft.

A total of 1,056 trajectories were obtained on the study day, and 972 valid trajectories were analyzed from the combined data source. Each trajectory was projected onto the LGA graphic network to locate the origin and destination of aircraft movement on the surface, as well as the set of consecutive nodes identifying each taxi route. Table 2 summarizes the statistics on routing options for each distinct OD pair (gate-runway pair). For the total of 92 distinct gate-runway pairs, about 80% of the OD pairs had, at most, 3 routing options, and 1 unique routing option was used for almost half of the OD pairs (40 of 92, or 43.5%). It can be concluded that the level of variety on routing options for most gate-runway pairs was relatively low. Thus, one routing option was assumed for each distinct gate-runway pair. (The option of alternative routings will be discussed in future work.)

TABLE 2 Summary of routing options for distinct gate-runway pairs

Route Options	# of OD	%	Cumulative %
1	40	43.5%	43.5%
2	19	20.7%	64.1%
3	11	12.0%	76.1%
4	4	4.3%	80.4%
5	6	6.5%	87.0%
6	1	1.1%	88.0%
7	2	2.2%	90.2%
8	2	2.2%	92.4%
9	3	3.3%	95.7%
11	1	1.1%	96.7%
12	1	1.1%	97.8%
15	2	2.2%	100.0%
SUM	*92*	*100%*	

Historical operation performance was analyzed by first extracting timing information from the projected track data. Table 3 presents the statistics of taxiing times from 18:00 to 19:00 on the study day. By averaging the taxiing time of 66 flights during this hour, the mean taxiing time was 9.04 minutes with a standard deviation of 5.36. It can be observed that departure flights spent 8.5 minutes more, on average, during the taxiing phase than the arrival flights and showed higher standard deviation as well. The total taxiing time of all active flights within this hour adds up to 596.95 min, roughly 9.95 hours total. Such historical performance metrics are compared in details with the outcome of the proposed model in next section. The average taxi speed was 14.6 knots during this hour and 13.7 knots during the study day. Analysis of flights without taxiing delay shows that the average speed was as high as about 30 knots. This speed is used in numerical experiments for the optimization problem.

TABLE 3 Mean value and standard deviation of historical taxiing time (18:00-19:00)

	Total	Dep	Arr
Mean	9.04	12.91	4.40
Std	5.36	3.84	2.38

VII. NUMERICAL RESULTS

There were 66 flights operations during the study time period of 18:00-19:00 on December 14, 2010, including 36 departure flights and 30 arrival flights. A total of 13 planning windows were optimized consecutively, with 5 to 6 flights modeled during each planning period. On average, the computation time for solving the mathematical programming for each planning horizon took about 5 seconds. All computations were performed on a Dell computer with an Intel Core i5 processor (3.20 GHz), 8 GB RAM, and a 64-bit operating system.

The historical scenario was compared with the calculated scenario from the model. In this case, the weight factor was set as 0.8, a parameter that can be changed by preference of the decisionmaker. Metrics were defined to evaluate the performance of the algorithms. The performance metrics were divided into two categories: excessive taxiing time and runway throughput.

A. Taxiing Time

For the 66 flights, the surface track data showed that all 36 departures took off on Runway 4 and 30 arrivals landed on Runway 31. For the sake of the simplicity, the estimated ready time of the first flight was set as the reference time (0 min). The first aircraft in this hour was a departure aircraft, so the reference time was set as its target off-block time. After completing the optimization, the total taxiing time of the 66 flights was reduced from 596.9 minutes to 130.1 minutes; thus, a 7.7-hour reduction of excessive taxiing time was observed.

Figure 3 and Figure 4 shows the comparisons of taxiing times before and after the RTI-ASOM for individual departure and arrival flights, respectively. Based on the historical scenario, the average taxiing time of all active flights in this hour was 9.04, with a standard deviation of 5.36. After implementing the RTI-ASOM, the taxiing times of the flights were improved significantly, as illustrated by the blue lines in both figures, presenting much lower and consistent taxiing times. Overall, the average taxiing time was reduced to 2.0 minutes per flight, with a standard deviation of 0.65.

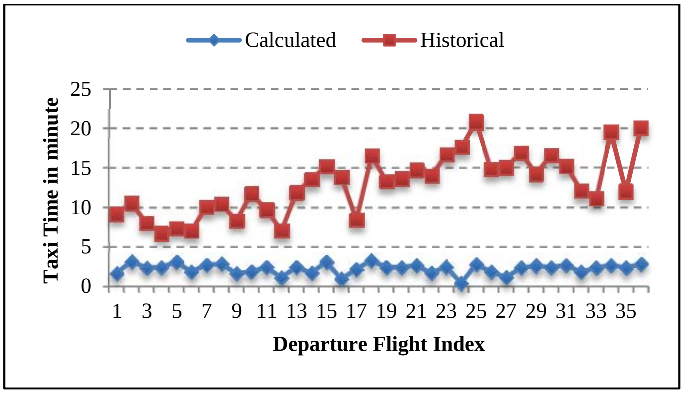

Figure 3 Calculated vs. historical taxiing time for departure flight

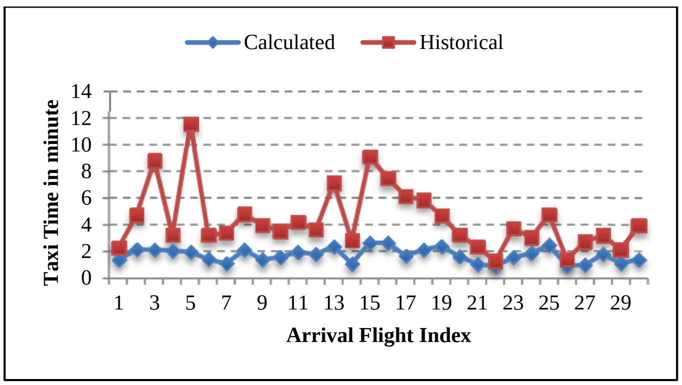

Figure 4 Calculated vs. historical taxiing time for arrival flight

Table 4 summarizes the statistics comparing departure and arrival flights before and after the implementation of RTI-ASOM. The performance of arrival and departure flights for the taxiing phase both were improved, with less average taxiing time and smaller standard deviation. Compared with arrivals, departure flights had a higher average taxiing time (12.91 min) before and now present a greater improvement—an average 10.7 minutes reduction per flight.

TABLE 4 Statistics of taxiing times for departure and arrival flights

Dep	*Calcul-ated*	*Histo-rical*	**Arr**	*Calcul-ated*	*Histo-rical*
Mean	2.24	12.91	*Mean*	1.72	4.40
STD	0.65	3.84	*STD*	0.53	2.38

As shown in Figure 5, by strategically holding the flight and controlling the releasing time, excessive surface delay in the historical data were shifted from the taxiway and runway to the gate, leaving more space on the surface for efficient operations. Gate-holding, instead of waiting on a taxiway and end of runway with engines on, saves fuel consumption and mitigates environmental impacts to the local area and global climate. Figure 5 shows the optimal holding time with respect to the estimated ready time and excessive taxiing time reduced for each departure flight. The total gate holding time for 66 flights added up to 682 minutes, and the reduction of excessive taxiing time was about 485 minutes. It is also of great importance that RTI-ASOM provides advisories on the time control along each flight trajectory and guarantees a conflict-free surface movement environment.

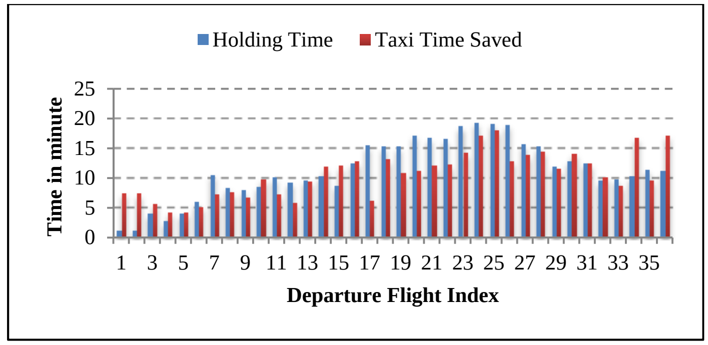

Figure 5 Holding time and excessive taxiing time reduced for departure flight

B. *Runway Throughput*

To evaluate the performance of runway throughput, the last runway usage of the last flight in the planning horizon was compared for both the historical and optimized scenarios. With respect to the estimated ready time of the first flight, the last runway access time in historical data was 79.6 minutes, but was reduced to 73.6 minutes with RTI-ASOM. The 6-minute time saved for runway usage could accommodate at least 4-7 more flights. For a congested airport such as LGA, the 6-minute saving in peak hours yields capacity for accommodating more flights and more efficient use of scarce airport facilities.

VIII. CONCLUSIONS

In this research, an integration of airport surface improvement with runway, taxiway, and gate management was prepared for NextGen with more automation of surface movement control and making 4-D trajectory operation applicable. Given the earliest ready time for a mix of departure and arrival flights, the model in this study optimizes aircraft surface movement by maximizing runway throughput and minimizing total taxiing times, subject to the operational constraints of ready time limits, conflict-free constraints, recursive planning requirements, precedence constraints, minimum separation requirements, and speed limits. A decomposition algorithm was introduced to use dynamic programming to extract the potential options of runway sequence and then to obtain a 4-D trajectory of aircraft taxiing by solving an MIP optimization problem. A set of modules was coded with VBA, and a user-friendly interface was built in Excel to realize and automate the solution algorithm.

The experimental analysis of surface optimization algorithms was conducted using one-hour track data on December 14, 2010, at LGA. The outcomes show a total reduction of 7.7 hours of excessive taxiing time for 66 flights. Average taxi-out time of departure flights was reduced by 83%, and average taxi-in time of arrival flight was reduced by 61%. To achieve such reductions, gate holding of 682 minutes was realized. During this one-hour experiment, runway throughput measured by the last runway access time of the last flight also showed significant improvement. The 6-minute time savings for runway usage could accommodate 4-7 more flights in one hour. The improvement of these performance metrics yields more efficient operations on the airport surface, and the RTI-ASOM with 4-D trajectory of taxiing helps improve the predictability of airfield and airspace operations.

Limited by rare surface data, assumptions were made for unknown variables such as target off-block times for departures and earliest landing times for arrivals. A rich data source could help researchers conduct further in-depth analysis and expand the application of this integrated model. Future research includes (1) relaxing the unique-taxi route assumption and capturing multiple routes options in the modeling; (2) conducting sensitivity analyses of taxiing speeds; (3) evaluating the environmental impacts of RTI-ASOM; and (4) comparing this management strategy with other control regimes for airport surface operations.

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