An Optimal Metroplex Routing Paradigm For Flexible Flights

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In this paper a metroplex routing scheme with its entire flexible flight operation simulation system is presented. In order to implement the optimal metroplex routing algorithm, a network data structure is constructed based on navaids, fixes, waypoints and jet routes. The shortest path algorithm and minimum dynamic cost path algorithm are applied to calculate the optimal route in different scenarios. Moreover, the other functional modules in the integrated simulation system are also introduced, which include Flexible Flight Selector, Airspace Concept Evaluation System, Candidate Flight Plan Estimator, Multicenter Traffic Management Advisor and the airport/runway balancer. The simulation system is the very first successful integrated platform of these NASA and university developed tools for metroplex study. The simulation results are demonstrated at the end, which verify the benefits of the flexible flight operations and the optimal metroplex routing scheme by showing the considerable total delay reduction.

I. Introduction

Air transportation system inefficiencies are found when air traffic demand exceeds system capacity. The resulted flight delays thus increase operating costs of airlines, air traffic controllers'

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workload, and the probability of passengers missing connecting flights. Moreover, the air traffic demand is expected to continue its rapid growth in the future. The Federal Aviation Administration (FAA) estimated in 2007 that the number of passengers is projected to increase by an average of 3% every year until 2025 [1]. Most of the traffic demand increase will occur in metropolitan areas where there are two or more large airports. The Joint Planning and Development Office (JPDO) defines this kind of region, with a group of two or more nearby airports whose arrival and departure operations are highly interdependent, as a *metroplex*. The New York Metroplex (N90 TRACON), for example, consists of John F. Kennedy (JFK) airport, LaGuardia (LGA) airport, and Newark (EWR) airport, as well as several smaller airports. The study in [2] shows that the traffic in most metroplexes has increased significantly over the past years and the N90 metroplex has the heaviest traffic demand. Future traffic growth will put current facilities under extreme pressure. Therefore how to reduce delays at metroplexes is critical.

The metroplex phenomena was first studied by Atkins in San Francisco bay area and N90 [3, 4]. It was showed that metroplex phenomena will affect the total capacity of the metroplex airport system. In [5] Atkins et al. presented a metroplex definition based on several measurable dimensions and proposed an initial framework to study the nature of metroplexes. Donohue et al. studied the airports in N90 early in 2008 [6, 7] and the authors considered the status of each airport in terms of the markets served, seat capacity, delays and other features. McClain and Clarke [8] designed the metric for metroplex clustering analysis. The dependencies and impacts of the three major airports JFK, LGA and EWR in N90 metroplex were analyzed by DeLaurentis et al. in [9, 10], where several metrics and models were developed to provide insights for planners to formulate policies and strategies that streamline metroplex operations and mitigate delays.

Although the metroplex concept and its corresponding metrics have been studied by a few researchers, there are very few of them discussing how to increase the metroplex efficiency and reduce the total delay. In this paper an integrated flexible flight operation simulation platform is introduced, which consists of multiple functional modules such as routing, scheduling, flexible flight selection, and flexible flight candidate plan estimation. Particularly, the routing module is described in detail. The metroplex routing algorithms are implemented by constructing a network data structure from the waypoints (navaids, arrival fixes, metering fixes, etc.) and jet routes. Two algorithms are applied with and without the en route traffic congestion constraint respectively. To the authors' best knowledge this work is among the very first integrations of the complete flexible flight operation simulation platform with multiple well developed NASA and university developed tools.

The rest of this paper is organized as follows. The second section introduces the concepts of metroplex and flexible flights. The overview of the integration platform and its functional modules is also presented. Section III shows how the network data structure is established and the metroplex routing algorithms with/without traffic congestion constraint are applied. Section IV shows the simulation results of N90 metroplex and Section V concludes the paper.

II. Overview

A. Metroplex and flexible flight

A *metroplex* is a region with several close airports which share traffic resources such as airspace and ground transportation. More rigorously, a metroplex consists of several close airports with consequential dependencies. Each metroplex includes the airports, the flights and ground traffic between them, the airline companies, and Air Traffic Control (ATC) services etc. In this paper N90 metroplex is investigated with its three major airports serving New York City metropolitan area.

A *flexible flight* is routed towards a metroplex instead of a pre-determined destination airport. Unlike the regular flight having a fixed destination airport, when the flexible flight approaches the decision boundary of the destination metroplex, it will receive the instruction of which runway of which airport to land in. The flexible flight operation is based on those passengers who do not have strong preference on arriving at a specific destination airport in a metropolitan area. More details about flexible flight operation can be found in [11]. To operate a flexible fight from its take-off to landing includes two parts. The first part is to route the flexible flight towards its destination metroplex. The second part is when the flexible flight approaches the decision boundary of the metroplex, it will be scheduled to a certain runway in the metroplex according to all the airport conditions. In practice the "decision boundary" consists of a series of metering fixes [12].

The concepts of metroplex and flexible flights have two main advantages. First, it allows the air traffic control system to maximize resource utilization (runways, in this case) in an otherwise tightly constrained system. Second, it allows users to experience less delay when accessing a metroplex area.

B. Platform overview

In order to simulate the flexible flight operations and evaluate the optimal routing algorithm, an integrated platform is created, which consists of several functional modules. The data flow diagram in Figure 1 illustrates how these modules interact with each other.

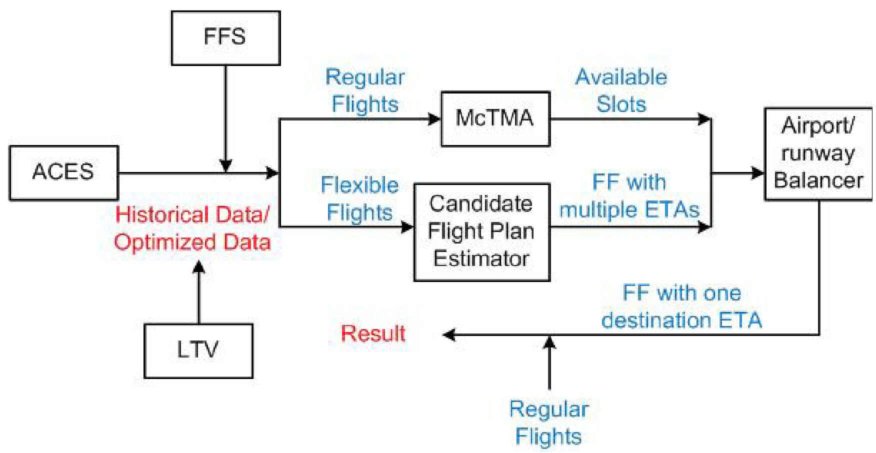


Fig. 1 The data flow diagram of the integrated model.

Besides the optimal routing module called the Linear Time-Variant optimization module (LTV), there are five major functional modules in Figure 1. They are ACES (Airspace Concept Evaluation System), FFS (Flexible Flight Selector), Candidate Flight Plan Estimator, McTMA (Multi-center Traffic Management Advisor) scheduler and the airport/runway balancer.

ACES [13] is a NASA software tool that loads in the recorded or optimized flight plans and outputs the high accuracy simulated aircraft trajectory data with Airline ID, computer ID, aircraft type, weight category, origin airport, destination airport, the complete trajectory, ETA (Estimated time of arrival), airspeed along the trajectory, etc. The output aircraft trajectory data are classified by FFS into regular flights and flexible flights.

FFS module is developed by Purdue University, which takes the same set of aircraft trajectory data and designates the flexible flights based on aircraft total travel distance, destination airport, percentage of connecting passengers and other factors (please see [11] for detail). It categorizes the aircraft trajectory data into regular flights which are fed into McTMA and flexible flights which are loaded into Candidate Flight Plan Estimator.

The aircraft trajectory data of flexible flights are sent to the Candidate Flight Plan Estimator. Each designated flexible flight only has one recorded trajectory. Based on this existed trajectory, the new candidate flight plans and corresponding ETAs are estimated for the same flexible flight to all the other destination airports inside the metroplex (see [11] for detail).

McTMA [14] takes the regular flights and runs the scheduler to find out the available time slots (holes) for the flexible flights. These holes are then sent to the airport/runway balancer that will decide which destination airport a flexible flight should land in. Then each flexible flight only has one determined destination airport and one flight plan. These determined flexible flight plans are fed back into McTMA where they are scheduled together with the regular flights (Fig. 2).

The airport/runway balancer is a university developed plug-in for McTMA, which loads in all the candidate flight plans for each flexible flight from the Candidate Flight Plan Estimator and only selects one flight plan for every flexible flight. All the selected flexible flight plans are sent back to McTMA where they are scheduled.

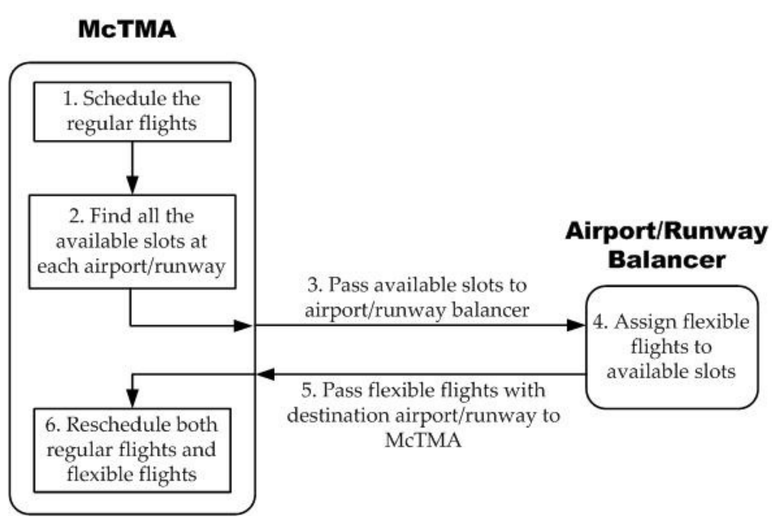


Fig. 2 Interactions between McTMA and airport/runway balancer.

III. Data Structure and Optimal Routing Algorithms

A. Jetway Network Data Structure

A jetway network data structure is constructed to design the optimal routing algorithm under en route traffic congestion constraint. The data structure is built from navaids, fixes, waypoints and jet routes provided by the Future ATM Concepts Evaluation Tool (FACET) [15] as shown in Figure. 3.

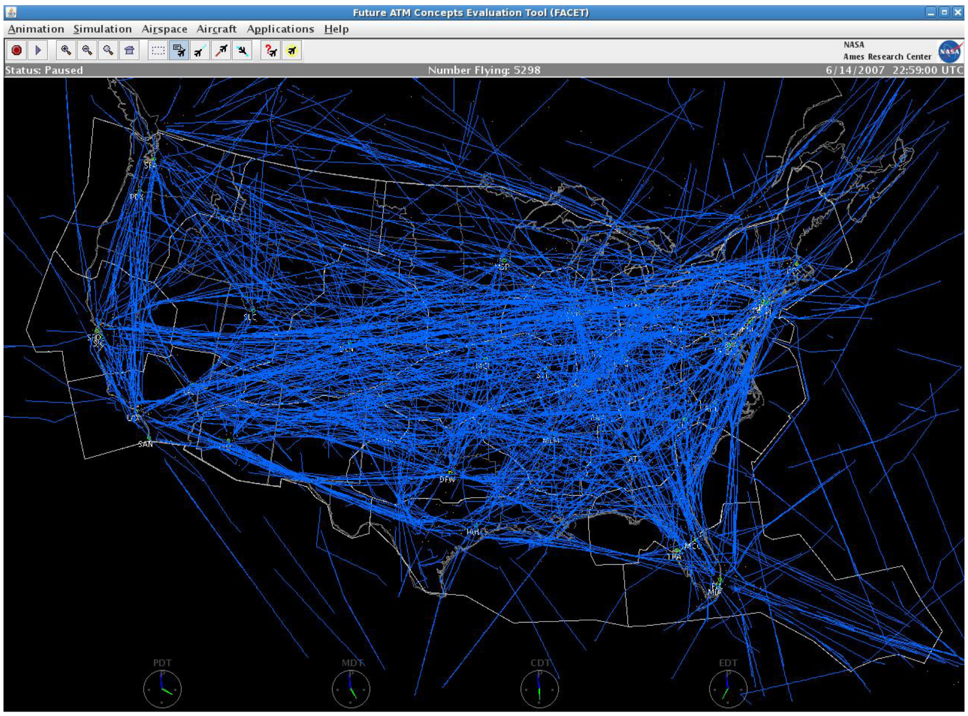
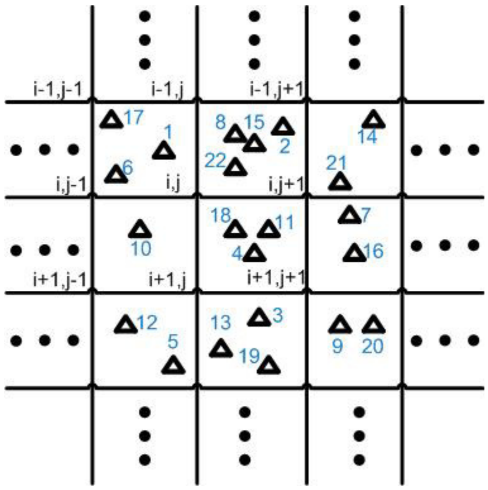


Fig. 3 The waypoints and jet routes provided by FACET.

Hash index is used to maintain the data structure, i.e., the nodes (all kinds of waypoints) and edges (jet routes) respectively. For ease of demonstration, only the waypoint Hash index is described here. The Hash key of each waypoint is the rounded positive latitude-longitude pair. In other words, each waypoint's latitude and longitude are transformed to their absolute values and then rounded into integers. The resulted positive integers are stored in a Hash key pair (lat, lon).

From another perspective, applying this kind of Hash index is to divide the US airspace into grids. Each grid is a square with four corners whose latitude and longitude are integers as shown in Figure. 4 (a), where i and j are integers. When there is a new waypoint to be added or removed, first calculate its Hash key pair and decide which grid it is in. As *floor rounding* is used to obtain



Hash Index	Waypoints
...	
i-1, j-1	1, 6, 17
i-1, j	2, 8, 15, 22
i-1, j+1	14, 21
...	
i, j-1	10
i, j	4, 11, 18
i, j+1	7, 16
...	
i+1, j-1	5, 12
i+1, j	3, 13, 19
i+1, j+1	9, 29
...	

Fig. 4 (a) Hash indexed grids enhance the maintenance of waypoints; (b) Waypoints are stored in a sorted Hash table H.

(lat, lon) from the absolute latitude and longitude, if the waypoint exists in the data structure, it should be in the grid with top-left corner coordinates $(i, j) = (lat, lon)$. Therefore only the existed waypoints $\mathrm{WP}_4, \mathrm{WP}_{11}, \mathrm{WP}_{18}$ in this grid (see Figure. 4 (a)) need to be checked instead of checking all the waypoints in the whole data structure. This is an example of the benefit of Hash index and this method substantially enhances the speed of maintaining waypoint data records.

The Hash table H corresponding to the grid in Figure. 4 (a) is kept with sorted Hash key pair as shown in Figure. 4 (b). The grids are saved in ascending order of the first integer of the Hash key pair, and with the same first integer, the grids are recorded in ascending order of the second integer of the Hash key pair. The waypoints in each grid are recorded under the Hash key pair (lat, lon) which is also actually the top-left coordinates (i, j) of the corresponding grid. If there is no waypoint in a grid, that grid will not be stored in the Hash table.

B. Optimal Routing Algorithms

In this section, the routing algorithm without en route congestion constraint is first described. The edge weight is great circle distance which is constant. The shortest path algorithm is applied to find the optimal route for each aircraft. Then the en route congestion constraint is taken into account and the minimum dynamic cost path algorithm is adopted to find the optimal route in a time-variant weighted network. In this research project, the implemented minimum dynamic cost path algorithm is called the Linear Time-Variant optimization moduler (LTV).

1. *Optimal routing without en route congestion constraint*

The network data structure constructed in Section III is used for performing the optimal routing algorithm. When the routing algorithm does not take the dynamical traffic congestion into account, the weight of each edge is the great circle distance between two waypoints which is time-invariant. Therefore the Dijkstra algorithm [16] is adopted to find the optimal route. For regular flights, the algorithm is applied between origin and destination airports. For flexible flights, the routing algorithm terminates at the metroplex "decision boundary" (metering fix).

2. *LTV - the Linear Time-Variant optimization algorithm*

To introduce the timely changing en route traffic congestion constraint, the edges intersecting those congested areas will be assigned with additional penalty weights. The time-variant congestion penalty weight will be summed up with the great circle distance weight for each edge and stored in the network data structure. The dynamic congestion information can be retrieved from air traffic controllers. The minimum dynamic cost path algorithm in [17] is implemented to calculate the optimal route with time-variant edge weights.

IV. Simulation

To evaluate the benefits of flexible flight operation and the optimal routing module, actual flight data into N90 metroplex was tested by the integrated model. The simulation was performed on the historical data of November 7, 2008 at 3 major airports of N90 (JFK, LGA, EWR). The Aircraft Situation Display to Industry (ASDI) data set contains all types of air traffic such as commercial aircraft, general aviations and air taxis.

First of all, without the LTV optimization, different percentages of flexible flights were compared in order to study the advantage of flexible flight operation in N90. 0%, 10%, 20%, 30%, 40% and 50% flexible flights were selected by FFS out of the historical flights and directly sent to McTMA scheduling, in which the 0% case with no flexible flights is the evaluation baseline. Figure 5 and Table 1 show how total delay changes according to the percentage of flexible flights. As the percentage of flexible flights increase, the total delay of the three major airports decreases almost linearly. With the flexible flight operation concept, airport/runway balancer reduces the total delay by re-scheduling a flexible flight to the less congested airport. Compared to the baseline case (no flexible flight), the total delay reduction reaches 29.4% with 50% flexible flights.

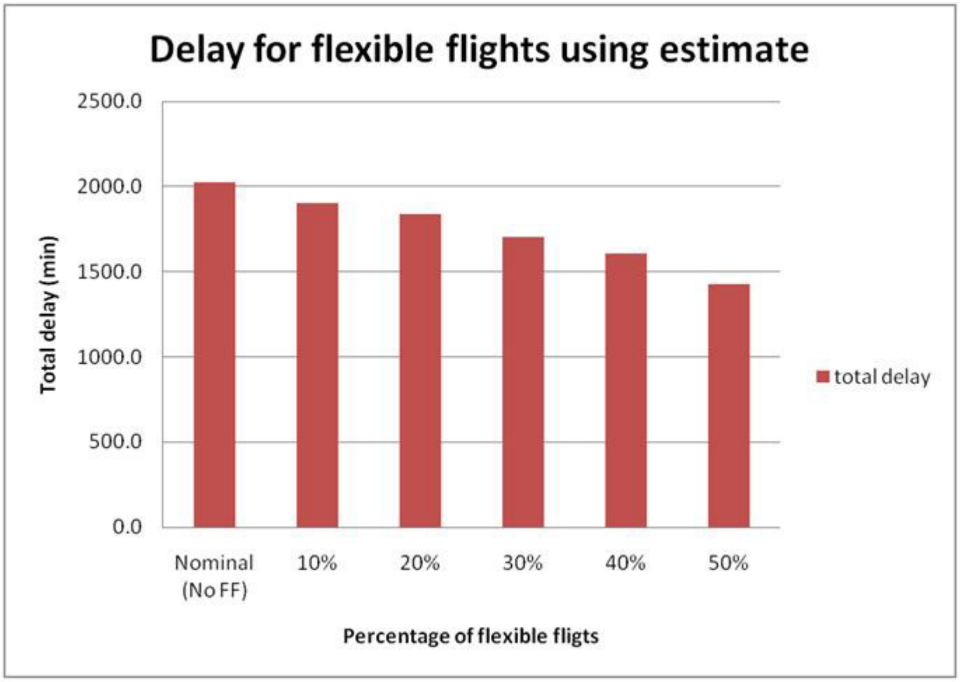


Fig. 5 Total delays for various flexible flight percentages into N90 on November 7th, 2008.

Table 1 Delay reduction (in minutes) for various flexible flight percentages into N90 on November 7th, 2008.

	KEWR	KJFK	KLGA	Total	Reduction
Nominal (No FF)	610.1	948.6	466.3	2025.0	
10%	586.6	1001.4	316.2	1904.2	-6.0%
20%	547.9	975.3	313.3	1836.5	-9.3%
30%	414.7	967.0	322.4	1704.2	-15.8%
40%	377.4	825.5	406.2	1609.1	-20.5%
50%	389.3	586.4	453.4	1429.1	-29.4%

The result of the second study is shown in Figure 6, where with LTV optimal routing and flexible flight operation (FFO) on/off, the comparison of four different combinations is illustrated. Without flexible flight operation, LTV reduced the total delay at the three airports from 2025 minutes to 1,830 minutes (9.5% reduction) as compared to the baseline case (no LTV optimization and no flexible flight operation). Without the LTV, applying flexible flight operation to 30% of the flights in historical data (30% are flexible flights, 70% are regular flights) gives about 300 minutes total delay reduction because the FFO well balanced the runway resource. In summary, combining LTV optimization and flexible flight operations has the largest delay reduction (536 minutes reduction from 2025 minutes). The simulation in Figure 6 shows that both LTV optimization module and flexible flight operation are beneficial to the metroplex in terms of reducing total delay.

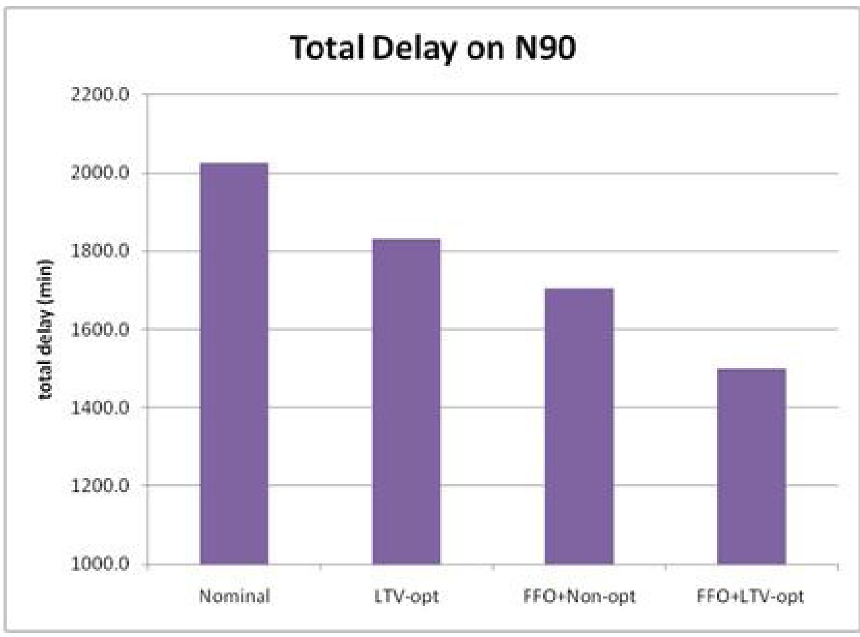


Fig. 6 Total delay comparison for four simulation combinations on November 7th, 2008 traffic.

V. Conclusion

In this paper the concepts of flexible flight and metroplex are presented. To increase the efficiency and reduce the total delay of the metroplex airports, an integrated flexible flight simulation platform is developed, which includes multiple functional moduels. The major contributor for totaly delay reduction is the optimal routing module based on the jetway network data structure. All the other modules are briefly introduced. The numerical result shows the benefits of both the flexible flight operation and the optimal routing module. The developed integrated simulation system can be considered as the framework of further metroplex studies.

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