A Novel Approach to Automated Merge 4D Arrival Trajectories for Multi-parallel Runways

Man Liang, Daniel Delahaye, Xiao-Hao Xu

[EN-I-027] A Novel Approach to Automated Merge 4D Arrival Trajectories for Multi-parallel Runways

$^{+}$ LIANG Man *, **   Daniel DELAHAYE **   XU Xiao-hao *

* College of Civil Aviation
Nanjing University of Aeronautics and Astronautics
Nanjing, R.P China
man.liang@enac.fr, xuxhao2008@sina.com

** MAIAA Laboratory
Ecole Nationale de l'Aviation Civile
Toulouse, France
daniel.delahaye@enac.fr

Abstract: This paper reports on the research status of automated merging 4D trajectories for multi-parallel runways operations in complex terminal area. In order to simultaneously reduce delay and increase capacity in metropolis airport with multi-parallel runways, based on the classic Point-Merge route structure, a novel Multiple-Points-Merge (M-PM) route system is firstly proposed. It consists of multi-layers on the sequencing legs for different categories of aircraft with H, M and L, and a M-PM system for Beijing Capital international airport is built with lazy "8" topology. After that, a multiple-objectives function is discussed for this aircraft scheduling problem, operational constraints are analyzed in detail, a modelling strategy with sliding time window and simulated annealing algorithm is proposed for solving this real-time scheduling and sequencing landing problem. According to the relationship between aircraft entry time and the position of sliding time window, all arrival aircraft are firstly classified into 4 different status: planned, ongoing, active, and completed, and then in the sliding time window the aircraft with active or ongoing status are optimized with re-sequence and conflict detection and resolution (CD&R) process. Conflict detection (CD) is based on pairwise form to detect separation infringement between aircraft. There are two types of conflict, catching up conflict and converging conflict. Conflict resolution (CR) solve the detected horizontal conflict with speed adjustment, slot time control, and turning time control technique. In a future work, this novel M-PM system will be evaluated with real operational data.

Keywords: Air traffic management, automated merging, 4D trajectories, multi-parallel runways

1 INTRODUCTION

With the continuously high-increase in the traffic flows by 10.8% per year from 2006 to 2014, the on-time performance of flight in China is dropping dramatically from 81.48% to 68.37%. The reasons for this deteriorating on time performance (or delay) may lie on different factors, in China, it is found that the three main factors are from airlines, air traffic management and weather in year 2014. Actually, the unbalance between high traffic flow demand and the low airspace capacity is the key reason. In whole china airspace, only around 20% airspace is reserved for civil aviation operations, in terminal area (TMA) of the hub airports, its capacity is near saturated or even overloaded as well. Therefore, to efficiently plan for the super density operation in hub airport and robust the arrival and departure flows is an important issue for increasing capacity and reducing delay.

Facing this problem in complex TMA, in the United States, NASA's Super Density Operations research project is proposed. Its purpose is to enable significantly increased and robust throughput at the busiest airports and most congested metropolis while minimizing environmental impact. The concept provides for a transition from today's operations to a terminal system that eventually relies on automation for a large portion of routine operations (including scheduling, sequencing, spacing and separation) and suggests leveraging the complex problem solving abilities of humans to manage recovery from off-normal events [1]. In Europe, under the concept of Trajectory Based Operations in the SESAR program, a planning tool named Medium Term Conflict Detection and Resolution systems is designed to help controllers for managing a perfect synchronization of 4D arrival trajectories at tactical level [2]. Without a doubt, in the future air traffic management, the automation will play an important role in making arrival management robust.

In this paper, we present a novel approach for safe, efficient and automated merging of the 4D arrival trajectories to multi-parallel runways, named Multiple Points Merge (M-PM) Route Network, with taking into account the mixed application of RNAV (Area navigation) route and PM (Point Merge) System.

2 PARALLEL INSTRUMENT RUNWAY OPERATION

According to ICAO DOC.9643 – Manual on simultaneous operations on parallel or near-parallel instrument runways, there are four modes of operation concepts relating to simultaneous operations on parallel instrument runways:

- Mode 1: Simultaneous approaches to parallel runways with independent parallel instrument approaches.

- Mode 2: Simultaneous approaches to parallel runways with dependent parallel instrument approaches.

- Mode 3: Independent instrument departures from parallel runways.

- Mode 4: Segregated operations on parallel runways.

In Mode 1,2 and 4, there may be semi-mixed operations, i.g. one runway is used exclusively for departures (or approach) while the other runway is used for a mixture of approaches and departures, or there may be mixed operations, all modes of operation are possible in each runway. In our research, we focus on the arrival management, so the topic of study will limit to the problem of parallel instrument runway approach.

3 CONCEPT OF M-PM SYSTEM IN TMA

3.1 Classical PM System

PM system is a systematized method for sequencing arrival flows developed by the Eurocontrol Experimental Center in 2006. It is considered as a cornerstone block to support 4D and Free Flight concepts in the forthcoming years.

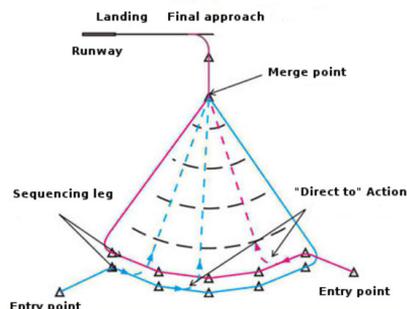As showed in Fig.1, a traditional PM system consists of two parts:

Figure 1 Classical Topology of PM System

1. a single point, denoted merge point, is used for traffic integration,

2. pre-defined RNAV routes, denoted sequencing legs, iso-distance and equi-distance from the merge point. They are dedicated to path stretching or shortening for each inbound flow and normally shall be separated by design vertically, laterally or both. Generally in vertical they are separated 1000 ft, the outer leg is located lower than the inner leg, in horizontal they are separated 2 NM.

In PM system, aircraft remain in lateral mode, after they enter the sequencing leg, they fly at an economical speed, and when *Direct to* instruction is reported at the optimum time, they perform a turn towards the merge point, then at another optimum time, they perform a CDA descent. The airborne separation between preceding and trailing aircraft is maintained only by speed adjustments ordered by controllers. Without heading instruction needed in PM system, the workload of controller is reduced dramatically, specially for the feeder controller who integrates the flow in the final approach phrase. PM system is also able to easily absorb the different volume of traffic demand in TMA. In low capacity period, its sequencing legs could be shorter, and in high capacity period, its sequencing legs could be longer. From this point of view, its route structure is very suitable for handling dynamic traffic demand.

3.2 Advanced PM System for Parallel Runways

The most important requirement from high density operation in metropolis airport is increasing its capacity, which means in a fixed time range, e.g. one hour, they could accept more aircraft to land on the runway. Because the makespan (duration of the whole sequencing) of all arrival aircraft depends on the wake turbulence separation, it is very interesting to shift the position of aircraft in the landing sequence to achieve a maximum runway throughput, to reduce congestion and subsequent delays.

However, it is not easy for the approach controller to shift the aircraft position under a high density operation environment. Generally, controllers have only a 45 minutes time horizon to assign and perform the necessary control actions to deliver an aircraft to a particular position in the landing sequence. What is more, the complex terminal area is an extremely dynamic environment, where arrival aircraft have to descend to runway and departure aircraft have to climb to the cruising level, so one small re-sequencing aircraft action could increase extremely the workload of controllers. Therefore, it is interesting to find a good way to help the controller to easily shift the position of aircraft without increasing their workload.

If we consider the traditional track change strategies, we can find that they are usually based on the
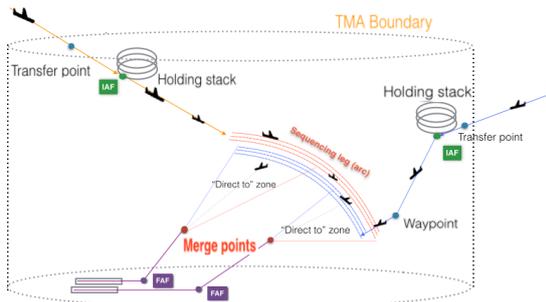
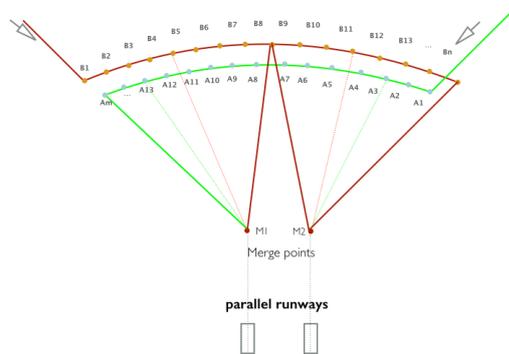Figure 2 Advanced PM System for Parallel Runways

Figure 3 Transformation of M-PM System

technique of heading change to execute some actions, such as left or right path stretch, left or right route offset, analytical turn or direct to a way-point. These techniques normally instruct the aircraft to change their headings frequently, to deviate from their planned route, so they really add workload for both controller and pilots.

Here, we are considering to design an efficient topology to integrate the arrival flows to parallel runways using PM system. As showed in Fig.2, a M-PM system for two independent parallel runways is designed. Aircraft from different directions arrive to the sequencing legs. There are 3 parallel flight layers for a group of aircraft coming from the same entry point, "Heavy" aircraft will choose the higher level, "Medium" aircraft will use the middle level and "Light" aircraft will enter the lower level, all of the three layers have a unique projection on horizontal level.

According to the distance between the runways, we could also design different M-PM topologies on the horizontal level, examples are shown in Fig.3, the advantage of this kind of topology is that arrival aircraft can easily change the runway. Furthermore, more complex M-PM topology, like lazy "8" shape, could be designed in consideration of operational constraints on specific airport.

3.3 A M-PM System for BCIA

In this paper, we take Beijing Capital International Airport (BCIA) as a design case, because later our research will continue work on it. BCIA ranked the second busiest airport in the world, there are three parallel runways: 18R-36L, 18L-36R, and 19-01. An independent parallel departures are used in all of these three runways, and runway 18R-36L and 19-01 are used with independent instrument parallel approaches. Referring to the operational data of Beijing TMA, it is found that arrival flows come mainly from the south, where there are 4 points of entry: JB, BOBAK, VYK and DOGAR. On the north, there are only 2 points of entry: KM and GITUM.

Basing on the RNAV procedures in the published standard instrument arrival chart (STAR) for RWY 36L/36R/01, we design a novel topology of arrival routes based on PM system, see Fig.4. In our new STAR, the approach routes are indicated separately by colour dark blue, light blue, purple and orange. Two shallow zones indicate the airspace for merging the aircraft separately to P1 and P2. P1 corresponds to runway 18R-36L and P2 corresponds to runway 18L-36R. Aircraft on P1 and P2 have 300 meters vertical separation. Red area with letter P means it is a prohibited area. Four standard holding procedures are designed on waypoints KM, JB, GITUM, DOGAR. Aircraft from the north follow the route GITUM-W15-
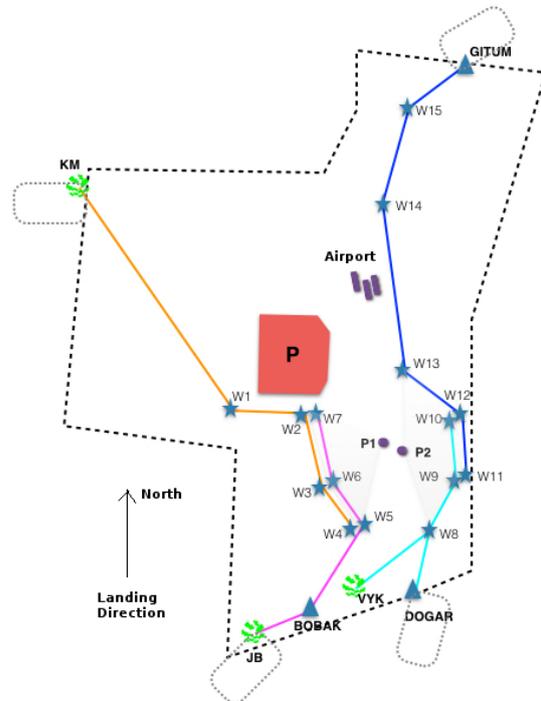

Figure 4 Beijing Arrival Chart with M-PM System

W14-W13 to arrive at merging zone of P2, aircraft from the west follow the route KM-W1-W2 to arrive at merging zone of P2, aircraft from south are separated into two groups, one group of aircraft follow JB-BOBAK-W5 to the merging zone of P1, the other group of aircraft follow VYK-W8 and DOGAR-W8 to the merging zone of P2. Aircraft on sequencing legs W2-W3-W4 or W5-W6-W7 will merge to P1 initially, then land on the runway 18R-36L. Aircraft on sequencing legs W10-W9-W8 or W13-W12-W11 will merge to P2 initially, then land on the runway 19-01.

4   MATHEMATICAL MODEL FOR PM-BASED AIRCRAFT SCHEDULING PROBLEM

4.1   Assumptions

For better implementation of our concept for the future air traffic control arrival management system, some basic assumptions have to be clarified. Firstly, taking into account operational reality, a sliding time window strategy will be applied to search a quick and near-optimal solution in a reasonable running time to face the super density flow situation. Secondly, different requirements from various stakeholders will be considered, such as air traffic control, airlines and airport, consequently the optimization objective function should better balance their different interests. Finally, the runway assignment problem will not be discussed.

4.2   Objective

A lot of research works have been done to study the problem of scheduling aircraft in TMA. [3] studied the scheduling problem of maximizing runway throughput under CPS (Constrained Position Shifting). [4] investigated a sequencing algorithm to take account of airline priorities. While, at the same time, some researchers attempted to find the trade-offs between different stakeholders' interests. In [5], it is indicated that: firstly, the significant improvement in the average delay could be achieved through re-sequencing under CPS. Secondly, in most case the re-sequencing using CPS improves both the makespan and the average delay when compared to the FCFS solution. Thirdly, on average maximizing the throughput only resulted in modest increases in the fuel costs.

Based on the analysis above, in our case we choose to simultaneously optimize three objectives:

1. minimizing the makespan of all aircraft on multi-parallel runways , maximizing the throughput.

2. minimizing the average delay.

3. minimizing the number of conflicts.

The multi-objectives function is defined as below:

$$z = Min\{\alpha \sum_{j=1}^{m} S^j + (1 - \alpha)(\frac{1}{n}) \sum_{i=1}^{n} (t_i - ETA_i) + \sum_{i=1}^{n} C_i\}, \quad (1)$$

where n is the number of flights, m is the number of parallel runways, t_i is the actual arrival time of flight i on the runway, ETA_i is the estimated time of arrival of flight i on the runway, S^j is the makespan of flights on runways j, C_i is the duration of conflicts with aircraft i, finally its value have to be zero after the conflict resolution process, α is the control parameter, if we more focus on delay, its value could be smaller, if we more focus on throughput, its value could be bigger. This control parameter could be dynamically changed, according to the severity of delay on the airport, so as to control the flow of arrival flights.

4.3   Operational Constraints

4.3.1   Maximum number of position shift in the sequence

The CPS problem was first proposed by Dear [6]. The maximum number of position shifts allowed is denoted by k, and the resulting environment as a k-CPS scenario. It has been noted that the reasonable values of k for CPS might be 1, 2, or 3. The restricted deviation from the FCFS order helps maintain equality among aircraft operators and also make air traffic controller more possible to shift the position of flight. In almost all current ATC automation systems, very limited overtaking is allowed, or only 1 position shift is usually used, due to the nature of our M-PM route topology, a more relaxed position shift is allowed, a slightly bigger value of k will not impose too much influence on the workload to controller. Here we could choose k equal to 2 or 3.

4.3.2   Arrival Time windows

The Estimated Time of Arrival (ETA) of flight at the entry point of TMA can vary. Normally the earliest time of arrival is usually limited to 1 minute before the ETA because of the resultant fuel expenditure, but if we consider mostly average delay decrease for arrival flights, then 3 minutes allowed time advance is feasible [5]. The latest arrival time is determined either by fuel limitations or by the maximum delay that a flight can incur, in our case, we want to minimize the makespan of all the arrival aircraft, so the latest arrival time constraint is always weaker than the the earliest time constraint. Here we choose the maximum delay of 10 minutes for the constraint of latest arrival time.

Table 1 Distance-based Aircraft Minimum Separation (unit: NM)

Preceeding \ Trailing	A380	Heavy	Medium	Light
A380	3	6	7	8
Heavy	3	4	5	6
Medium	3	3	3	5
Light	3	3	3	3

Table 2 Time-based Equivalent Minimum Separation with a Reference Speed of 240 knots (unit:second)

Preceeding \ Trailing	A380	Heavy	Medium	Light
A380	45	90	105	120
Heavy	45	60	75	90
Medium	45	45	45	75
Light	45	45	45	45

4.3.3 Minimum aircraft separation

Firstly, ICAO regulates the minimum spacing between landing aircraft to avoid the danger of wake turbulence. It is a distance-based separation under radar control environment. We also have to consider approach radar separation between two successive aircraft with the same category of wake turbulence, so in total the required aircraft minimum separation in TMA is listed in Table.1. If we assume a reference velocity, then distance-based separation could be transferred to a time-based separation, which is convenient for conflict detection. Referring to the performance of commercial aircraft with Medium and Heavy category, as well as considering the safety between entry and exit of TMA, a 240 knots is chosen as a reference speed, then the minimum time-based wake turbulence separation in TMA could be calculated, the results are showed in Table.2.

Secondly, there are some safety related requirements and operation procedures relating to dependent parallel instrument approach. The successive aircraft on adjacent ILS localizer courses on final approach tracks should not be less than 2.0 NM. Each pair of parallel approaches has a "high side" and a "low side" for vectoring to provide vertical separation until aircraft are established inbound on there respective parallel ILS localizer course, the high-side altitude should

be 1000ft above the low side at least until 10 NM from the threshold.

4.3.4 Maximum turning time on sequencing leg

With the nature of our M-PM topology, the aircraft on the sequencing legs have to turn before the end of sequencing leg.

5 MODELLING TECHNIQUE

5.1 Overall Framework

RHC, also named Sliding window or Rolling horizon, will be applied to dynamically solve the arrival management problem in complex TMA. RHC is a very effective on-line predictive control strategy, it is a nonlinear control policy that handles input constraints, output constraints, and a variety of control objectives. With RHC, we solve an optimization problem at each time step to determine a plan of action over a fixed time horizon, and then apply the first input from this plan, at the next time step we repeat the planning process, solving a new optimization problem, with the time horizon shifted one step forward.

In our case, as illustrated in Fig.4, the overall time horizon of 24 hours is firstly divided into smaller time horizons of prediction with different start times. The difference between two consecutive start times is named roll period. According to the relative relationship between the aircraft life cycle and the Sliding time window in the whole timeline, we classify the status of aircraft into 4 types: Completed, On-going, Active and Planned. *Completed* means that the aircraft's trajectory is already fixed. *On-going* means some part of the aircraft trajectory is still on the Sliding time window, some part of their trajectory is not changeable while some part of their trajectory are changeable. *Active* means the aircraft trajectories could be changed. *Planned* is the rest part of aircraft who are not belong to any types mentioned before. After that, those aircraft with *Active* and *On-going* status will be selected to enter the optimization procedures inside the sliding time window.

In the optimization procedures, it consists of two key steps: the first step is to sequence the aircraft, the second step is to merge the arrival flow without conflict. According to the objectives of this scheduling problem, we could shift the position of the aircraft, change the speed, change the entry time in the TMA, change the turning time on the sequencing leg etc., all these parameters which could be changed are called decision variables. Once the trajectories of the aircraft are changed, we recalculate the objective, repeat this procedures until achieving an optimal or near-optimal result. The process could be resolved by application of heuristic algorithm such as Simulated Annealing algorithm.
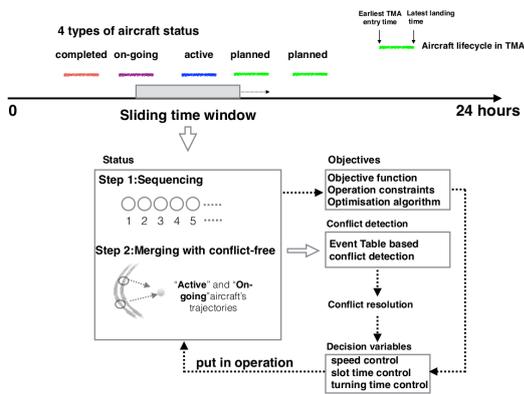
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Figure 5 Modelling Method with Sliding Window

5.2 Conflict Detection and Resolution

Two aircraft are considered to be in a conflict if their horizontal separation is less than the minimum aircraft separation or if their vertical separation is less than 1000 ft. Here, We separate the horizontal conflicts into two types: *catching up* conflict and *converging* conflict. When the aircraft fly from the entry point of TMA to the end point of sequencing leg in the PM system, a *catch up* conflict should be detected between two successive aircraft. Then a *converging* conflict should be detected for aircraft turning to the merge point. All the aircraft in the merging zone should be kept laterally separated, which means once aircraft a is flying to arc $A1$, it will block other aircraft turning to arc $A1$. When a is continuing to arc $A2$, then arc $A1$ is released for other aircraft.

Once a conflict is detected, we proceed to the conflict resolution. The approach controllers usually solve the conflict with speed change, heading change, altitude change, or even holding procedure and flow con-
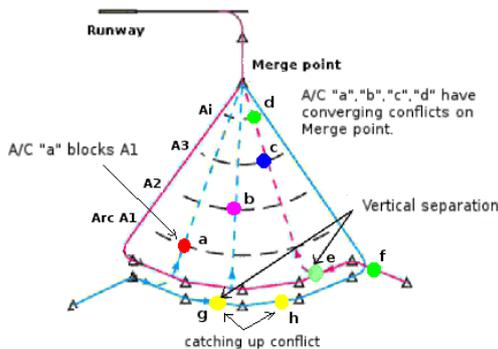
trol when there is a long delay in the TMA. For the sake of robustness, in our PM system, only three parameters could be changed for solving the horizontal conflict: speed, entry time, and turning time on the sequencing leg. The overall strategy for solving the multiple horizontal conflicts is rules-based.

6 CONCLUSION AND FUTURE WORK

In this paper, a concept of automated merging 4D trajectories for multi-parallel runways operations in complex terminal area is proposed. Extending from the idea of classic Point-Merge route structure, a novel Multiple-Points-Merge (M-PM) route topology was discussed. Then, a mathematical model is built to solve the aircraft scheduling problem. After that, a modelling method with sliding time window and conflict detection and resolution strategy is explained. In the future work, we will collect real data from BCIA to evaluate this novel M-PM system.

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Figure 6 Conflicts Detection in PM system