Potential Operational Benefits of Multi-layer Point Merge System on Dense TMA Operation Hybrid arrival trajectory optimization applied to Beijing Capital International Airport

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Hybrid Arrival Trajectory Optimization Applied to Beijing Capital International Airport

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***Abstract*—4D Trajectory optimization in dense terminal control area is one of the most challenging problems in air traffic management research. In order to efficiently and robustly land more aircraft at Beijing Capital International Airport (BCIA), one of the busiest airport in the world, a novel trajectory operation model is proposed, i.e. Multi-layer Point Merge (ML-PM) based Autonomous Arrival Management System. This paper aims at the evaluation of its potential operational benefits in terms of flight efficiency and runway throughput. Horizontal and Vertical profiles of ML-PM route network are introduced, the objective and constraints of this optimizing mathematical model are analyzed, especially the speed change profile and the conflict detection mode for merging zone. Then a case study is made by simulating arrival flows under three different operational modes: baseline, traditional point merge, and the ML-PM. Finally, the results show that rational arrival sequence and conflict-free trajectories are generated in ML-PM system, the benefits gained are very positive. Comparing with baseline and the traditional point merge system, ML-PM system shows good performance on flight time, fuel consumption, CO_2 emission. The saving of fuel with ML-PM system is expected around 26838 Yuan per hour at BCIA compared with baseline scenario by numerical simulation. Furthermore, more flexible sequence position shift and continuous descent are possible in ML-PM system, and it is capable to handle the high-density operation environment.**

Keywords-air traffic management; arrival management; trajectory optimization; point merge; multi-layer on sequencing leg

I. INTRODUCTION

Increasing the efficiency of flights arriving at busy airports is one of the most challenging topics in air traffic management research. On the one hand, new techniques and procedures from on-board systems provide a great probability for commercial aircraft to follow an optimal descent profile or a direct flight route to any desirable waypoint, such as Continuous Descent Approach (CDA) procedure and RNP route, which will lead to less fuel consumption and noise. However, these procedures highly depend on the aircraft performance and the operational environment. Without planning, they will normally increase the complexity of air traffic, consequently complicate the tasks of separation assurance for the air traffic controller, ultimately impact negatively on the airspace capacity. On the other hand, nowadays the separation assurance in dense terminal maneuvering areas (TMAs) is still mainly managed by air traffic controller in tactical level, even though Arrival Management (AMAN) system is implemented at some busy airports for helping the controller to sequence and schedule arrival traffic. Traditional baseline radar vectoring technique and step-by-step level-off procedure are frequently used for handling aircraft arrival from different TMA entry points to Final Approach Fix (FAF). Such type of procedure makes it impossible for aircraft to execute an optimal descent profile. Moreover, traditional control procedures prevent further increasing the airspace capacity due to the voice communication workload of the final approach feeder controller.

In order to match the requirements in dense TMA operation, improve flight efficiency and increase runway throughput simultaneously, numerical researches have been done through different approaches. One solution is to develop advanced trajectory operations models which could integrate the continuous descent in dense TMA. A successful example of this is the SESAR project Point Merge (PM) system. PM is a systemized method for sequencing arrival flows developed by the EUROCONTROL Experimental Centre in 2006. It is now one of the ICAO Aviation System Block Upgrades and is referenced as a technique to support continuous descent operations (Doc 9931) [1]. Performance of PM was analyzed both by real time simulations and real operation environments. The results show that less workload for controller and more predictable and efficient trajectory for flight will be gained [2,3]. Another solution is to make the air traffic control procedure more automated or robust, transfer from the sole-based separation assurance system to airborne-based spacing system, so as to continuously increase airspace capacity. In fact, research on automation of Air Traffic Management (ATM) has been performed in a long period. On the operational level, decision support tools were developed to help controllers at busy airports, e.g. Center TRACON Automation System (CTAS), developed by NASA-AMES in the early 4D trajectory study period, provides automation assistance to air traffic controllers in achieving acceptable aircraft sequencing and separation [4]. On scientific research level, references [5,6] studied the automated separation assurance and arrival management in TMA by using speed change, heading change, route stretching, or time-constraints on specific merging fix, with weather in consideration.

Under the concept of Trajectory Based Operation (TBO), in order to further improve the arrival management at congested airport, we propose a novel trajectory operation model, its initial study could be found in references [7,8], the concept is optimizing the arrival sequence in busy TMA to efficiently and robustly land more aircraft by grouping Heavy/Medium/Light aircraft to different layers on the sequencing leg of PM, namely Multi-Layer PM system (ML-PM). This research idea combines the benefits of PM and the automated separation assurance techniques, aims to make the arrival trajectory at congested airport more efficient, orderly, and safe. In reference [7], Beijing Capital International Airport (BCIA), which ranks the second busiest airport in the world with a peak volume of 1600 flights per day, was selected for the case study. Its PM-based advanced route network on horizontal profile, the mathematical model that generates optimal trajectories with complex dynamics and constraints were built, and initial numerical study was performed to test the hybrid optimizing algorithm, which combines Receding Horizon Control with Simulated Annealing algorithm (RHC-SA), under different density operation environment.

This paper is an extension of our previous works, and aims to make an assessment of potential benefits gained by this novel ML-PM based autonomous arrival management system in order to be used for reference during possible future development. We enhanced the previous studies by considering flight altitude changes and speed changes.

The content of this paper is organized as follows: Section 2 makes a brief introduction to the formulation of the overall study framework, including the ML-PM route network for BCIA, the objective and constraints of optimizing problem, and the conflict detection model. Section 3 describes the scenarios used in the case study, including three different operational models: baseline, traditional PM and the ML-PM. Section 4 presents the results and the analysis on fuel consumption, flight time, flight distance, landing interval, delay to the different cases, as well as advantages of ML-PM system. Finally, section 5 presents the conclusion and prospections.

II. Framework of ML-PM Based Arrival Trajectory Optimisation

A. ML-PM Route Network for BCIA

As showed in Fig. 1, a classic topology of PM system in horizontal plan consists of a point, named the merge point, and the pre-defined legs, named the sequencing legs which are

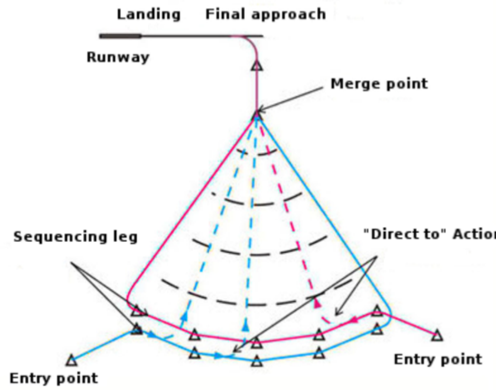

Figure 1. Classic Topology of PM System

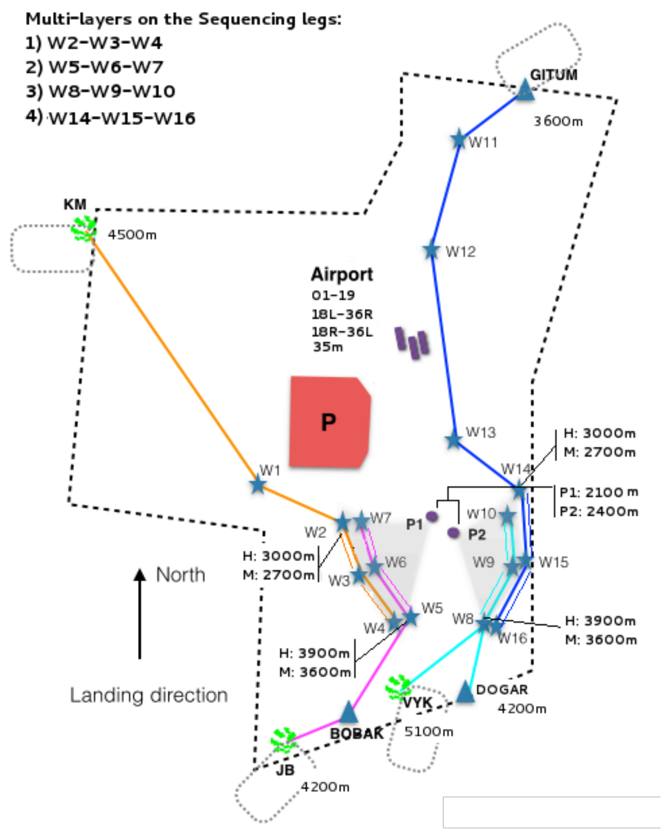

Figure 2. ML-PM Route Network for BCIA

equidistant from this point [9]. Controllers issue "Direct to" instruction to pilot to merge the aircraft to the merge point.

In respect of real operational environment, refer to the published RNAV STAR chart and the instrument approach chart. The ML-PM based arrival route network was built for the prevailing landing direction facing north at BCIA.

On horizontal profile design, as shown in Fig. 2, firstly all the real entry points in the Beijing TMA are kept, there are KM, JB, BOBAK, VYK, DOGAR, and GITUM, two merging points P1 and P2 are designed separately for runway 18R-36L and 19-01, then because of limited airspace in the south of Beijing TMA, as well as a prohibited area P near airport, a lazy "8" shape layout of sequencing legs is selected to separately merge the traffic flow from different directions to P1 or P2. In total, there are five routes available for arrival flights, and remark that aircraft from GITUM, VYK and DOGAR could only merge to P2 and then land on runway 19-01, aircraft from KM and JB could only merge to P1 and then land on runway 18R-36L.

On vertical profile design, as shown in Fig. 2, firstly flight altitudes on the five entry points of TMA are kept as real operational value in reference of control transfer agreement between adjacent sectors, then according to the distance from the threshold of the runway and the continue descent profile of aircraft, the designed altitude at P1 and P2 are 2100 meters and 2400 meters, respectively (in China, controllers use meters instead of feet as the units, 300 meters ≈ 1000 feet). As mentioned before, our ML-PM will have multi-layers for different categories of aircraft, therefore we have to consider the available and rational flight altitudes on sequencing legs of our ML-PM system. In the Beijing TMA, the available flight altitudes for designing multi-layer are very limited, then if the designed altitude is too high, aircraft on the top layer can not efficiently descent to the target altitude on the merge point P1 or P2, if it is too low, aircraft need consume more fuels to level off on the sequencing leg. In order to perform a continuous descent, in our case, we design two layers to group Heavy and Medium aircraft, on W2-W3-W4, 2700 meters for Medium, 3000 meters for Heavy, on W5-W6-W7, 3600 meters for Medium, 3900 meters for Heavy, because the transition layer in BCIA is between 3000m to 3600m, so the lowest altitude on W5-W6-W7 (i.e. 3600m) is 600m higher than the highest altitude on W2-W3-W4 (i.e. 3000m). Following the same rules, we design W8-W9-W10 with 3900m for Heavy and 3600m for Medium, W14-W15-W16 with 3000m for Heavy and 2700m for Medium. Remark that there was no Light aircraft operating at BCIA in reference of the historical flight data, furthermore, there are few A380 landing at BCIA, it is not necessary to design one layer for them, instead they could join the layer for Heavy aircraft.

B. *Mathematical Optimization Model*

The mathematical optimization model of this arrival sequencing and scheduling problem is described as below: a large set of aircraft f_i $(i = 1, \dots, n)$arriving at TMA will land on two runways separately. The objective of optimization problem is to generate a conflict-free and efficient trajectory for each of them, with consideration of reducing the average landing interval and delay. The decision variables are: 1) the estimated time of arrival (ETA) at the entry point of TMA, denoted t_i^e, 2) the entry speed of aircraft at the entry point of TMA, denoted v_i^e and 3) the turning time of aircraft on the sequencing leg, denoted t_i^{turn}.

The constraints consist of operational constraints and constraints on decision variables. Firstly, for safety reason, at any moment the spacing $d_{i,j}$ between two successive aircraft i and j should not be less than the ICAO required minimum radar control separation $s_{i,j}^{radar}$ and the wake turbulence separation on radar control situation $s_{i,j}^{WT}$. Secondly, the adjusting range to v_i^e is limited by ±12%, the arrival time window to t_i^e is [-5mins, +5mins]. All the decision variables are changed in a discrete way [7]. Thirdly, in order to simplify the study problem, at the same time prepare a close-to-real operation, the speed change profile is pre-defined. As shown in Fig. 3, each aircraft maintains the entry speed v_i^e from the entry point of TMA to a point which is 10 nm from the entry of PM, then it changes the speed to 220 kts (knots) for the "Medium" or 230kts for the "Heavy" on reaching entry point of PM, keeps this speed until turning action is triggered, after that, it continuously reduces speed to 150kts for "Medium" or 180kts for "Heavy" at the merge point P1 or P2, finally it reduces speed to 140kts on FAF and keeps this value until threshold of runway. Last but not least, the required constraints on flight altitudes at the significant points correspond to the vertical design of ML-PM route network.

In conclusion, the objective function is formulated as below:

$$
\begin{aligned}
&z = Min\{\alpha T + \beta D + C\} \qquad (1)\\
&T = \frac{m}{n} Max\{S^1, S^2, \dots, S^m\}\\
&D = \frac{1}{n}\sum_{i=1}^{n}(t_i^L - ETA_i^L)\\
&C = \sum_{i=1}^{n}(c_i^{node} + c_i^{link})
\end{aligned}
$$

Here, T denotes the average landing interval, D denotes the average delay, C denotes the calibrated duration of total conflicts, n is the number of aircraft, m is the number of parallel runways, S^i is the makespan of the landing aircraft for runway m, t_i^L is the actual landing time of flight i , ETA_i^L is the the estimated landing time of flight i , c^{node} is the calibrated number of conflict for flight i on the nodes, and the c^{link} is the calibrated number of conflict for flight i on the links. α and β is the user-defined control parameters. Here, C is intended to reduce to 0, therefore according to the importance among T, D and C, $\alpha = 0.0015$ and $\beta = 0.001$ are chosen in this study case, for mainly guiding the algorithm to generate a conflict-free trajectory.

C. *Conflict Detection*

The conflict detection is the core part in the trajectory optimization process. Traditional tree-based trajectory merging mode normally separates the conflict detection process into two parts, i.e. node conflict detection and link conflict detection. The node conflict refers to the conflict between aircraft from different routes merging to the same point at the same altitude. The link conflict refers to the conflict between aircraft on the same route at the same altitude. In our ML-PM route network, the merging zone conflict detection is very different from the conflict detect mode in the tree-based merging method. In order

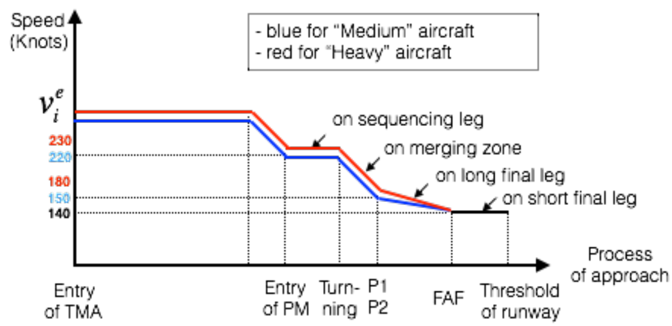

Figure 3. Speed profile of aircraft on the process of approach

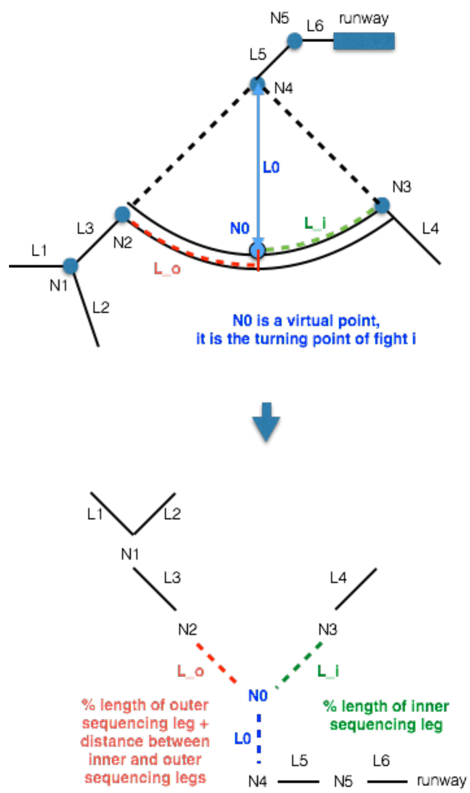

Figure 4. Virtual network of merging zone for the conflict detection

to make our detection process more unified in the whole framework, a detection method is improved on the base of reference [7], the ML-PM route network is transferred into a virtual tree-based route network for the horizontal time-based conflict detection, see Fig. 4.

Knowing that after aircraft turn from the sequencing leg, during the process of approach to the merge point, they have to be laterally separated based on the distances from the merge point. In this new mode, a virtual point N0 is built for fixing the common distance L0 for the aircraft coming from different sequencing legs and merging to the same point. Two dynamic links L_i and L_o are built to represent the duration of flight on the sequencing leg, their lengths depend on the decision variable t_i^{turn}. Note that N0 is not a geographic point, it represents the turning position of each aircraft on the sequencing leg.

III. CASE STUDY

A. Flight Efficiency Performance Index

The optimization objective described in the previous section is mainly related to the safety and the runway throughput from the point of view of the Air Navigation Service Provider (ANSP). In order to assess the potential benefits gained by the novel ML-PM system not only on safety but also on efficiency of commercial airliners, in this paper, three flight efficiency performance indices are selected: flight time, fuel consumption and CO_2 emission.

The accuracy of the estimated fuel consumption and CO_2 emission depends on the quality of the weather data (e.g. wind, temperature and air pressure), the aircraft performance (e.g. thrust, fuel flow), and the airlines' cost index (CI). Due to the lack of real radar surveillance data, meteorological data etc., as an alternative, we consider the average fuel flow to evaluate the potential benefits on the flight efficiency. The way to define the average fuel flow is: first, there are around 80% "Medium" aircraft landing on BCIA, 65% of which are A321 or B738. Then, based on the study of BADA model on A321 and B738 on approach descent profile, a prevailing fuel consumption 25 kg/min is selected as the common average fuel flow μ_a for all category of aircraft flying on Beijing TMA, consequently the fuel consumption J_i for flight i can be defined as in:

$$J_i = \int_{t_i^e}^{t_i^L} \mu_a dt \tag{2}$$

According to ICAO carbon emissions calculator methodology [10], the amount of CO_2 produced by burning an amount of aviation fuel for flight i could be calculated as:

$$E_i^{co_2} = 3.16 \times J_i = 3.16 \times \int_{t_i^e}^{t_i^L} \mu_a dt \tag{3}$$

B. Scenario Design

1) Baseline with penalty on conflict-resolution

In this case, a baseline scenario is built without the point merge system. A tree-based route network is built, see Fig. 5 (Baseline), radar heading vectoring techniques are supposed to be used on the maneuvering zones. In this scenario, we simulate the traditional baseline method by the way described as below: 1) the aircraft from different directions could only make the turning maneuver in the indicated maneuvering zone in order to avoid trajectories overlapping between different arrival routes; 2) a penalty of three minutes per conflict is added to the total flight time of each aircraft in order to simulate the baseline strategy used by controllers for conflict resolution.

As seen from Fig. 5, the main difference between the topology of baseline and that of PM is: the available deviation area for flight in baseline part is less than the merging zone in PM, which will induce different conflict resolution methods. In baseline scenario, less available solution could be gotten on the deviation area, alternatively more resolution will target on the adjustment of the entry time at the entry point of TMA, which may impose a negative influence on the adjacent control sector. While in PM scenario, due to more available holding solution on the sequencing legs, the adjustment on the entry time at the entry point of TMA may be less.

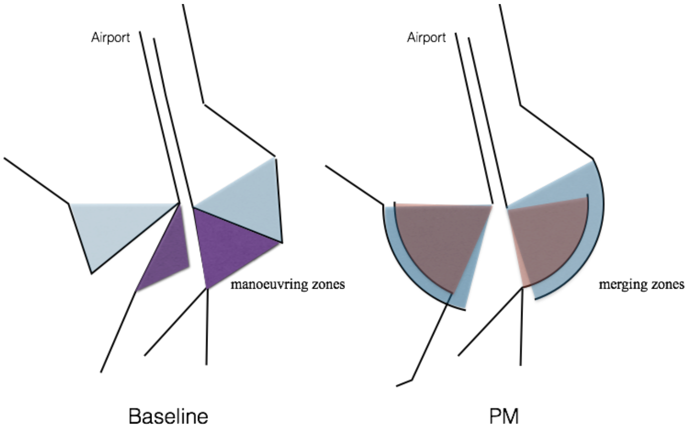

Figure 5. Two ways of merging arrival flows

2) *Traditional PM with unique layer on sequencing leg*

In this case, a traditional PM scenario is built with unique layer on sequencing leg, named PM-No group hereafter. Aircraft must keep the same altitude when they are on the same sequencing leg. Due to different speeds for the "Heavy" and the "Medium" aircraft, conflict must be detected on the sequencing leg between two successive aircraft.

3) *Advanced PM with multi-layer on sequencing leg*

In this case, a ML-PM scenario is built with multi-layer on sequencing leg, named PM-Group hereafter. Aircraft with the same category remain on their specific layer at the same speed, the conflict detection on the sequencing leg is not necessary, we only control the time separation between two successive aircraft on the same entry point of sequencing leg.

IV. NUMERICAL RESULTS AND ANALYSIS

A. *Data*

Based on the operational data at BCIA on Nov.6th 2015, a scenario simulation input data is prepared. There are 823 flights to land at BCIA in 24 hours, of which 78.5% are "Medium", 21.5% are "Heavy". 12.27% of the traffic come from KM, 17.98% from JB, 47.63% from VYK, 11.18% from DOGAR, and 10.94% from GITUM. The histogram of arrival rates at BCIA is presented in Fig. 6. On busy period from 10:00 to 24:00, the average number of arrivals is around 46 flights per hour, the runway throughput of BCIA is normally 88 flights per hour for both departure and arrival, according to the "2014 national civil aviation flights operating efficiency report" published by CAAC on May 2015[11]. In this paper, the arrival flights from 10:00 to 12:00 are analyzed to determine the potential operational benefits of ML-PM autonomous system.

B. *RHC-SA Hybrid Algorithm for Simulation*

N-step-ahead optimization approach (RHC) is applied to match the requirement of dynamic operational situation. A sliding window transfers the total 24-hours static optimization problem into several sub-optimization problems. According to the relationship between the life cycle of arrival aircraft and the timeline of the sliding window, arrival aircraft are divided into 4 statuses: completed, on-going, active and planned. After that, in each sliding window, Simulated Annealing algorithm is applied to generate the near-optimal trajectories for those aircraft with "active" status. Details of RHC-SA Hybrid Algorithm for simulation is described in reference [7]. In this paper, we just provide the parameter setting information used on this study case with timeline of 2 hours, see Table. I.

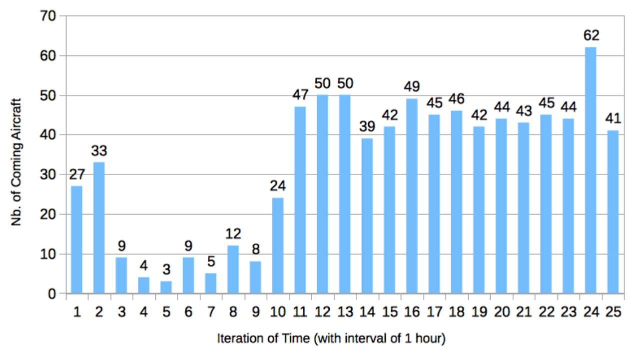

Figure 6. Histogram of arrival rates at BCIA on Nov.6th 2015

TABLE I. PARAMETERS CONFIGURATION OF RHC-SA

Elements	**Configuration setting**	
	Name of the parameters	***Value***
Sliding window	Size of the window	2400 seconds
	Window shifting interval	900 seconds
Simulated annealing	Initial temperature for heating	0.01
	Heating rate	1.1
	Maximum number of transition for heating or cooling	500
	Cooling rate	0.99
	Cooling stopping criterion	$T<0.0001*T_{init\_cool}$
	Neighborhood selection P_{Turn}	0.25
	Neighborhood selection P_{Speed}	0.5

C. Numerical results

This part lays out the numerical results for the different cases described in Section 3 scenario design. There are 93 aircraft to land at BCIA from 10:00 to 12:00, 64 aircraft land on runway 19-01, 29 aircraft land on runway 18R-36L. The overall results show that the ML-PM system has great potential to improve the runway throughput and flight efficiency simultaneously.

1) Conflict resolution

The conflict resolution on each sliding window is determined by SA algorithm. The performance of conflict resolution by SA in one sliding window is shown in Fig. 7. Calibrated number of conflict reduces from 144.33 to 0. During all the process of optimization, time-based separation between each pair of aircraft must not violate the 90s minimum separation condition on the merge point.

2) Flight efficiency

Tab. II shows the flight efficiency performance in three scenarios in terms of total flight time, total fuel consumption and the total CO_2 emission. PM-Group scenario is more efficient than the PM-No group and the baseline scenario. There is small difference between baseline and the PM-No group, the reasons are: 1) as discussed in the scenario design, the available deviation area is more limited in the topology of baseline, equal to only around 45% of the merging area in PM; 2) turning strategy for solving the conflict is limited for further improving the landing rate. Whereas, the difference between the PM-No group and PM-Group is larger, the application of segregated levels for different weight turbulence categories of aircraft is effective, and more aircraft could stay on the sequencing leg, which avoids large deviation from the initial trajectory. If we refer the average cost of fuel per flight per hour in 2014 in China with 23500 Yuan [11], the expected saving of fuel with ML-PM system is around 26838 Yuan per hour at BCIA compared with baseline scenario.

3) Runway throughput and delay

Tab. III shows landing rate and delay performance in these three scenarios. The runway throughput increases as the average landing interval decreases. In all the indices, the results of PM-Group are slightly positive compared to PM-No group and baseline. Aircraft in the PM-Group scenario could land fastest with minimum delay. More precisely, as a result of the numbers of aircraft at the TMA entries, around 65% aircraft will land on the runway 01-19, therefore two runways have different landing densities, in the next content, more detailed study results will be shown.

4) Performances of ML-PM system

PM-Group scenario simulates the ML-PM system. We will analyze it in view of both ATC and airlines.

Firstly, in view of ATC, we will discuss the conflict resolution performance followed by landing interval analysis on different runway, and then the position-shift sequencing technique.

Different decision variables are chosen for generating conflict-free trajectories. As shown in Tab. IV, we separate the adjustment on the initial values of decision variables into six levels based on the relative proportion on the adjusting ranges described in Section B, these levels are: no change, slight change (0-20%), little change (20%-40%), moderate change (40%-60%), high change (60%-80%), and strong change (80%-100%). For speed change, the main adjustment is on the range "strong change" followed by the range "moderate change", for ETA change, the main adjustment is on the range "strong change", for turning position on sequencing leg, most of the aircraft make the turning action on the range "slight change". The neighborhood selection strategy induces these searching results and the conflict resolution strategy is reasonable. Speed change is easy for the pilot to control, and we planned to let aircraft fly less distance on the sequencing leg if there is no conflict with other aircraft.

Parallel runway operation is analyzed as well due to different operation density. Runway 19-01 with 64 landing aircraft is more charged than runway 18R-36L. It takes 135 minutes for all the 64 aircraft to land on runway 01-19. However, the landing interval in runway 19-01 is 2.1 minutes, with 2.12 min less than runway 18R-36L. On the operational point of view, PM-Group really shows a good performance under high-density operation environment, see Fig. 8.

For safety reasons, the wake-vortex separation must be established between two successive aircraft landing on the same runway, generally the required time interval between them depends on their weights. First-Come-First-Served (FCFS) order is the most common approach to sequencing aircraft, under which aircraft utilize the runway in order of their estimated arrival times at the runway. One of the disadvantages of the FCFS schedule is that it may lead to reduced runway throughput due to large spacing requirements, therefore it motivates deviating from the FCFS sequence to achieve schedules that increase runway throughput, i.e. Maximum number of position shift (k-MPS) problem. k-MPS problem has been studied for a long period, and it has been noted that the reasonable values of k for CPS might be 1, 2, or 3, mainly because a slightly bigger value of k may impose huge workload to controller [12,13], and in almost all current ATC automation systems, a very limited overtaking is allowed, normally only 1 position shift. Due to the nature of our ML-PM route structure, a more relaxed position shift could be possible. As shown in Fig. 9, The maximum number of position shifts could reach up to 7, and this position shift could be easily handled only by the "turning" decision variable.

Secondly, in the view of airlines, we will discuss the continuous descent profile of aircraft in ML-PM scenario.

The descent rate of aircraft in ML-PM scenario is limited by flight performance, and on the final approach process, three degrees of descent gradient is applied to aircraft. If aircraft need to maintain an altitude or level-off during the process of continuous descent, its trajectory will present a short horizontal line. In Fig. 10, Axis x is "Time", axis y is "Altitude", descent trajectory is presented in blue line, one "medium" aircraft comes from entry point VYK, one "Heavy" aircraft comes from DOGAR, the level-offs of these two aircraft are relatively short

TABLE II. FLIGHT EFFICIENCY IN THREE SCENARIOS

Type of scenario	Total flight time (min)	Total fuel consumption (kg)	Total CO2 emission (kg)
Baseline	2358	58955	186297
PM-No group	2332	58307	184252
PM-Group	2221	55528	175471

TABLE III. CAPACITY AND DELAY PERFORMANCE IN THREE SCENARIOS

Type of scenario	Average Delay (min)	Make Span(min)	Ave. Land Interval (min)
Baseline	4.34	142.52	3.06
PM-No group	3.92	139.23	2.99
PM-Group	3.33	137.09	2.95

TABLE IV. DECISION VARIABLES IN ML-PM SCENARIO FOR GENERATING CONFLICT-FREE TRAJECTORIES

Level of adjustment	Percentage of aircraft on different decision variables		
	Speed	ETA	Turing
No change	15.05%	4.30%	8.60%
Slight change	10.75%	15.05%	26.88%
Little change	4.30%	12.90%	10.75%
Moderate change	20.43%	16.13%	19.35%
High change	12.90%	19.35%	13.98%
Strong change	36.56%	32.26%	20.43%

on the sequencing legs, and at the merge point P2, level-off for these two aircraft is not needed. Due to a near continuous descent and aircraft staying longer on higher altitude, less noise and fuel benefits could be expected.

The total descent profiles of all the aircraft are shown in Fig. 11. We could find out that aircraft from south maintain a very short moment after the entry points, aircraft from north maintain a relatively long moment, then if required, hold a while on the sequencing leg until there is no conflict with the preceding aircraft, after that, turn and descend to reach the designed altitude at the merge point P1 or P2, finally at the FAF intercept the localizer. Except that 29 aircraft to land on runway 18R-36L need to make a short level-off at the FAF, all the 64 aircraft to land on runway 01-19 execute a continuous descent from the sequencing leg to runway.

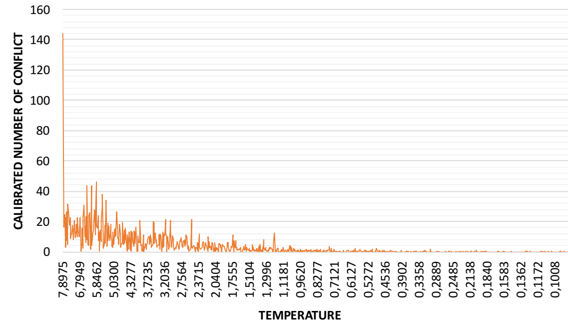

Figure 7. Example of conflict resolution by SA in one sliding window

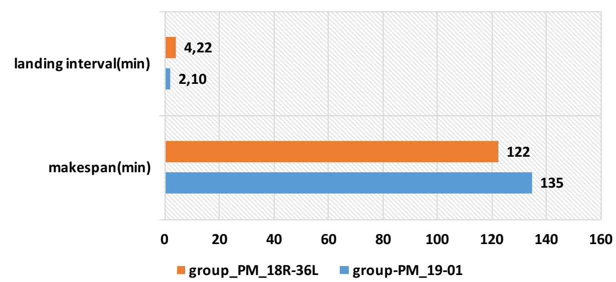

Figure 8. Landing interval and makespan performance in ML-PM scenario

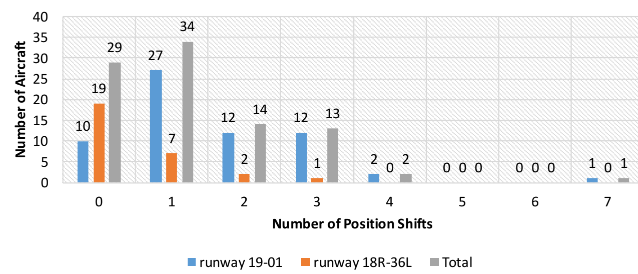

Figure 9. Position shift performance in ML-PM scenario

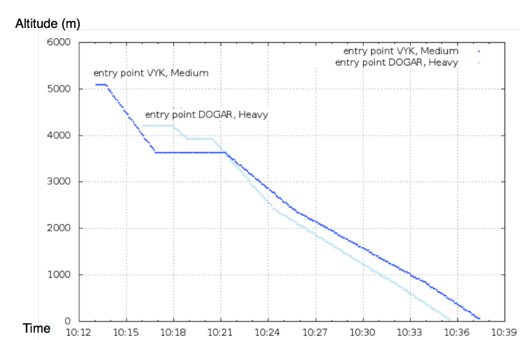

Figure 10. Descent profiles of two categories of aircraft

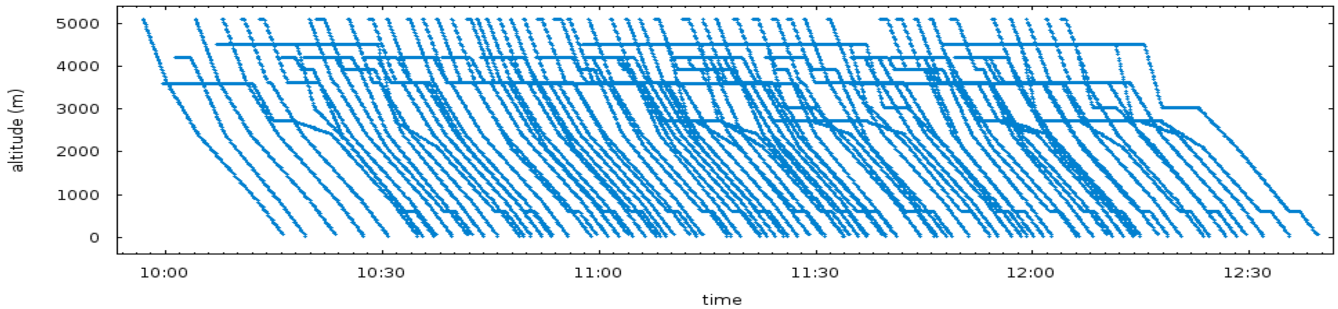

Figure 11. Descent profiles of all the aircraft in ML-PM scenario

V. Conclusion and Perspectives

The potential benefits analysis on ML-PM system is done in this paper. We have generated conflict-free trajectories on numerical simulation. The horizontal and vertical profile of ML-PM route network of BCIA are designed in detail, and continuous speed change profile is also described in order to simulate a continuous descent approach procedure. The related flight efficiency indices and the capacity indices are analyzed; the results have shown a significant improvement. However, this route network design model is limited to BCIA.

Our next researches will continue to demonstrate the interest of ML-PM system in two directions: 1) depth-study of current model by comparing with real operational data and increasing test benchmarks, enforcing the mathematical model, refining the calculation method of fuel and CO_2, 2) Breadth-study by refinement of the methodology in order to apply this route network design model to other busy airports having complex terminal airspace, discovering more possible combinations of PM elements to improve the parallel runway operation.

Acknowledgment

The author would like to thank anonymous experts for sharing their knowledge and giving us advices, Serge Roux for the visualization of the trajectories with Xtraj, and some colleagues in MAIAA lab for the language editing help.

References

[1] E. Hoffman, "Point Merge: improving and harmonising arrival operations with existing technology", 2011.

[2] D. Ivanescu, C. Shaw, C. Tamvaclis, and T. Kettunen, "Models of air traffic merging techniques: evaluating performance of point merge", 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), September 2009.

[3] L. Boursier, B. Favennec, E. Hoffman, A. Trzmiel, F. Vergne, and K. Zeghal, "Merging arrival flows without heading instructions", 7th USA/Europe Air Traffic Management R&D Seminar, July 2007.

[4] T. J. Davis, H. Erzberger, S. M. Green, and W. Nedell, "Design and evaluation of an air traffic control final approach spacing tool", Journal of Guidance, Control, and Dynamics, 1991, vol. 14, no 4, pp. 848-854.

[5] H. Erzberger, T. A. Lauderdale, and Y. C. Chu, "Automated conflict resolution, arrival management and weather avoidance for ATM", 2010.

[6] T. Prevot, J. Homola, H. Martin, J. Mercer, and C. Cabrall, "Automated air traffic control operations with weather and time-constraints", 9th USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), June 2011.

[7] M. Liang, D. Delahaye, P. Marechal, "A framework of point merge-based autonomous system for optimizing aircraft scheduling in busy TMA", 5th SESAR Innovation Days, Bologna, Italy, Dec 2015.

[8] M. Liang, "An agent-based approach to automated merge 4D arrival trajectories in busy terminal maneuvering area", Procedia Engineering, 2015, vol. 99, pp. 233-243.

[9] EUROCONTROL, Point Merge Integration of Arrival Flows Enabling Extensive RNAV Application and CDA Operational Services and Environment Definition, Version2.0. Eurocontrol Experimental Center, 2010.

[10] ICAO, "Methodology ICAO carbon calculator_v8-2015", May 2015 [http://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v8-2015.pdf]

[11] CAAC, "2014 national civil aviation flights operating efficiency report", May 2015 (in Chinese) [www.sked.cn/2014BG.PDF].

[12] R. G. Dear, The dynamic scheduling of aircraft in the near terminal area. Cambridge, Mass.: Flight Transportation Laboratory, Massachusetts Insti- tute of Technology, 1976.

[13] H. Lee, H. Balakrishnan, A study of tradeoffs in scheduling terminal- area operations. Proceedings of the IEEE, vol.96, (no.12), 2008, pp. 2081-2095.