An alternative path modelling method for air traffic flow problem in near terminal control area

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***Abstract*— Due to the increase in air traffic demand, the various airports experience heavy traffic congestion on the airport surface and airside operations. The demanding air transportation service is causing complicated air traffic networks which will affect the effectiveness and efficiency of airport operations. In order to reduce the adverse effect of getting air traffic delay or airport congestion, an alternative path modelling is proposed to resolve the traffic flow network problem by path coordination and aeronautical holding methods. This research considers the air traffic flow problem near the terminal control area to resolve the delay problem and conflict detection by using computational intelligence.**

Keywords- air traffic flow problem; an alternative path approach; operations research

I. INTRODUCTION

Terminal Traffic Flow Problem (TTFP) defined as considering the flight management among the air traffic infrastructure in near Terminal Manoeuvring Area (TMA) such as joint segments, air route, runways, aeronautical holding, runway, common guided path and arrival segments to optimise the air traffic network for reducing the air and ground congestion in near the TMA. Generally, the more air traffic load, the higher the chance of having air route congestion at the near TMA. If the congestion occurs in the real situation, flight delay will possibly happen which will affect the overall performance of the airport. The adverse weather condition will also create delay propagation throughout the air traffic network. In order to solve the mentioned problem, rescheduling of flight can be one of the methods [1]. However, the decisions of arrival path and aeronautical holding are limited to the traffic control regulation and the current air traffic situation, which makes the terminal traffic flow management more difficult [2].

The growth of traffic demand is significant nowadays due to a large number of people travel and trade across the world, while the air traffic infrastructure is limited [3, 4]. In addition, the air traffic networks are being more complex [5]. The demanding air transportation volume with the limited infrastructure and the complex traffic network causes difficulty in airport operations [6]. As a result, it is so important to manage the airport capacity well for improving the air transportation performance. Poor management of the above situation causing air traffic delay which will reduce the profit in both direct and indirect ways including the increased expenses on maintenance, fuel and crews [7]. Other than the above factor causing delays, including the lack of TCA capacity, adverse weather conditions or other uncertain factors also limited the air traffic performance [8, 9]. Hence it is crucial to constructing a TTFP model for reducing delay and maintaining a robust schedule. In reality, the pilots will be given some information including the position and number of holding circles, the time for each operation, the designated runway and the following air segments [8].

The TTFP model is one of the variations under Aircraft Sequencing and Scheduling Problem (ASSP) [4]. The primary consideration in the ASSP model is runway assignment and runway operation scheduling problem regarding safety, a multi-runways system, available runway resources and efficient allocation of approach routes [2]. The poor and inefficient coordination of terminal Air Traffic Control (ATC) may cause wastage of TCA capacity management [8]. Bianco, et al. [10] constructed the TTFP model with a no-wait-job-shop scheduling method to provide complementary information on ATC at a TMA. The TTFP framework is mainly focused on the wind direction, the actual air traffic network, air segment structure and the terrain constraints near a TMA. An efficient terminal traffic flow solution can improve both airlines' and airports' performance [8].

The contribution of this work is stated as follows. The proposed alternative path model is to determine an approach path for particular flights from a set of valid paths. In general, the traffic flow network is an directed acaylic graph. The enter route is usually unchanged since the air route network is fixed. Samà, et al. [8] proposed an alternative graph model to determine the transit nodes for all flights. Compared to their work, alternative path model mainly considers the path assignment problem and reduce the solution space significantly than routing approcah.

II. Formulation of an Alternative Path Approach for the Terminal Traffic Flow Problem

In this section, the TTFP model is proposed to resolve the air traffic flow problem at the near TMA. The TTFP schedule provides conflict-free scheduling by considering the path coordination and aeronautical holding methods. Approaching aircraft generates vortex which will affect the stability of trailing flights. Therefore, a longitudinal separation is considered to ensure traffic safety when approaching. Furthermore, the model provides aid to support ATC via computational intelligence, which can further reduce their workload in monitoring airborne traffic situation. Fig 1 presents the alternative path approach for TTFP model, while Fig 2 explains the path coordination approach when flights j and i may violate the longitudinal separation requirement. Fig 3 illutrates an aneronautical holding to extend the holding on air to allow a smooth schedule.

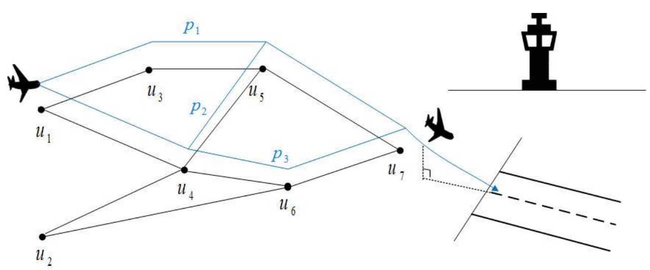

Figure 1. An alternative path approach.

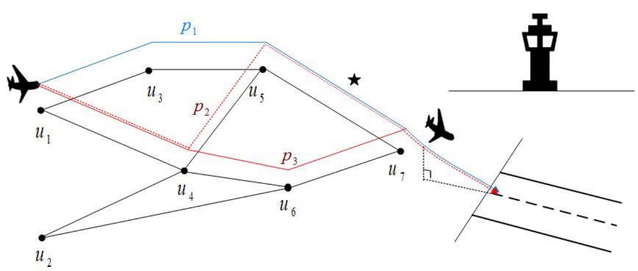

Figure 2. A conflict resolution using path coordination approach.

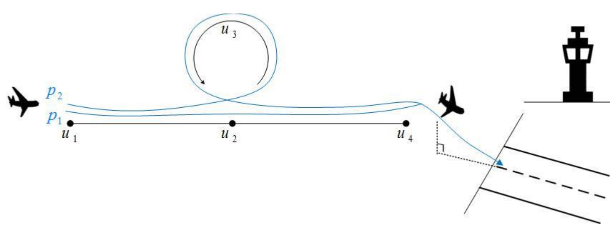

Figure 3. An aeronautical holding approach.

A. Assumption

The practical assumptions for constructing the robust TTFP model is listed as follow: (1) Because of the change of headwind direction related to the runway direction, the flights may change the approaching routes to ensure successive landing. (2) The approaching path is fallen into the decided horizon. (3) The transit time is expected to be imprecise as it is subjected to extreme weather conditions, turbulence and the resilience level of systemic and ATC schedule failure. (4) It is assumed that no emergency operations including bird strikes, precautionary landing and engine failure in the model. (5) Mono-aeronautical holding is considered in this model.

B. Formulation

The model herein is to determine the best approach path and the number of aeronautical holding to remain a smooth traffic flow schedule. The TTFP model is presented using a directed graph $G = (V, E)$. The set of nodes $u, v, \pi \in V$ illutrates the cross points or connection between air segment, while the set of arc $(u, v) \in E$ denotes the air route in near TMA. In the system, we consider that a set of approaching flights $i \in I$ bypasses a path p_i from a set of alternative paths P_i to reach the runway within a decision horizon. Two dummy nodes o and d indicate the first and end of the graph model. Each path $p_i = (o, u_1, u_2, \dots, u_{|P_i|}, d)$ illutrates the transit nodes from the origin node u_1 to the destination node $u_{|P_i|}$. In a traffic flow network, not all combinations of nodes can formulate a valid path. Therefore, we propose an alternative path approach which constrains the path selection from a set of valid/alternative paths P_i. In this connection, the set of nodes in the alternative path approach is the union of all transit nodes $V_i = \cup_{p \in P_i} V_i^{p_i}$ from a set of alternative paths P_i, while the set of arc in the alternative path approach is the union of all transit arc $E_i = \cup_{p \in P_i} E_i^{p_i}$ from a set of alternative paths P_i. The digraph G comprises $V_j, V_i \in V, E_j, E_i \in E$.

TABLE 1 presents the notations and decision variables of the deterministic model for TTFP. The decision variable $\varphi_i^{p_i}$ indicates the path assignment p_i for each flight $i \in I$. The decision variable z_{jiu} determines the sequence of each transit node. Therefore, the TTFP solution X is formulated by the combination of $\varphi_i^{p_i}$ and z_{jiu}. The weight coefficient of path selection $w_i^{p_i}$ denotes the weight different of a set of alternative paths, which equals to the number of aeronatical holding on the corresponding nodes. The completion time C denotes the completion time of last flights in a schedule or within the decision horizon.

TABLE I. TABLE I. Notations and decision variables

Notations	Explanation
i, j, k	Flight ID $i, j, k \in I$
u, v, π	Transit node $u, v, \pi \in V$
o	Dummy variable of origin node $o \in V$
d	Dummy variable of destination node $d \in V$
E_i	Estimated time of arrival in the terminal control area

$w_i^{p_i}$	The weight coefficient associated with the path selection $p_i \in P_i$
M	Large artificial variable
t_{iuv}	The mean travel time from nodes u to v for flight i
δ_{ji}	Separation time on air route between flight j and i
Decision variables	Explanation
X	A solution X is constructed by $\varphi_i^{p_i}$ and z_{jiu}
$\varphi_i^{p_i}$	1, if flight i is assigned to the path p_i; 0, otherwise
z_{jiu}	1, if flight j is before flight i on node u (not necessary immediately); 0, otherwise
$\tau_{iu}^{p_i}$	The arrival time on node u using path p_i for flight $i, \tau_{iu}^{p_i} \geq 0$
C	The completion time of the terminal traffic flow model

As mentioned in the above, the objective function is to minimise the number of aeronautical holding by using the weight coefficient of $w_i^{p_i}$ and the completion time of the approaching schedule as stated in Objective (1). Only one path can be selected from a set of alternative paths using Constraints (2), while the sequencial relationship between flight $i, j \in I$ on each transit node u by using the decision variable z_{jiu} using Constraints (3). Constraints (4) explained the relationship between $\varphi_i^{p_i}$ and z_{jiu}. The Constraints (5) restricts the sequence following the triangular inequality for flights $i, j, k \in I$. The appear time of each flight in the near TMA is equal to E_i. Therefore, the start time of each path is constrained by Equation (6). Constraints (7) control the arrival time on node u to be a positive real number if path p_i is selected, The set of node u belongs to elements of p_i. Constraints (8) compute the completion time of the schedule, while Constraints (9) determine the arrivel time from node u to node v with the consdieration of the transit time t_{iuv}. The longitudinal separation is imposed using Constraints (10). $\varphi_i^{p_i}$ and z_{jiu} are binary variables using Constraints (11) – (12) and Constraints (13) explained that the $\tau_{iu}^{p_i}$ is a positive real number.

$$F(X) = \min \sum_{i \in I} \sum_{p_i \in P_i} w_i^{p_i} \varphi_i^{p_i} + C \quad (1)$$

$s.t.$

$$\sum_{p_i \in P_i} \varphi_i^{p_i} = 1, \forall i \in I \quad (2)$$

$$z_{jiu} + z_{iju} \leq 1, \forall i, j, i < j \in I, \forall u \in V_j \cap V_i \quad (3)$$

$$\varphi_i^{p_i} + \varphi_j^{p_j} \leq z_{jiu} + z_{iju} + 1, \forall i, j, i \neq j \in I, u \in V_j \cap V_i, p_i \in P_i, p_j \in P_j \quad (4)$$

$$z_{iku} \geq z_{jiu} + z_{iku} - 1, \forall j, i, k, j \neq i \neq k \in I, u \in V_j \cap V_i \cap V_k \quad (5)$$

$$\tau_{io}^{p_i} \geq E_i \varphi_i^{p_i}, \forall i \in I, \forall p_i \in P_i \quad (6)$$

$$\tau_{iu}^{p_i} \leq M \varphi_i^{p_i}, \forall i \in I, \forall u \in P_i \quad (7)$$

$$C \geq \tau_{id}^{p_i}, \forall i \in I, p \in P_i \quad (8)$$

$$\tau_{iv}^{p_i} - \tau_{iu}^{p_i} \geq t_{iuv} - \mathrm{M}(1 - \varphi_i^{p_i}), \forall i \in I, p_i \in P_i, u, v, u < v \in E_i \quad (9)$$

$$\sum_{\substack{p_i \in P_i \\ u \in V_i^p}} \tau_{iu}^{p} - \sum_{\substack{p_j \in P_j \\ u \in V_j^p}} \tau_{ju}^{p} \geq \delta_{ji} - M\left(1 - z_{jiu}\right), \forall i, j, i \neq j \in I, \forall u \in V_j \cap V_i \setminus \{o, d\} \quad (10)$$

$$\varphi_i^{p_i} \in [0,1], \forall i \in I, \forall p_i \in P_i \quad (11)$$

$$z_{jiu} \in [0,1], j, i, j \neq i \in I, u \in V_j \cap V_i \quad (12)$$

$$\tau_{iu}^{p_i} \in \mathbb{R}^+, \forall i \in I, \forall p_i \in P_i, \forall o, u, d \in P_i \quad (13)$$

III. Computational Experiments

After formulation the TTFP model, we would like to obtain a set of statistical randomly generated instances to show the algorithm performance regarding the computational time in a set of variables manipulation. The instances came from an authorised API from *FlightGlobal* and which is the distribution of real data in April 2018 at The Hong Kong International Airport (HKIA). The generated instance follows the flight pattern in HKIA.

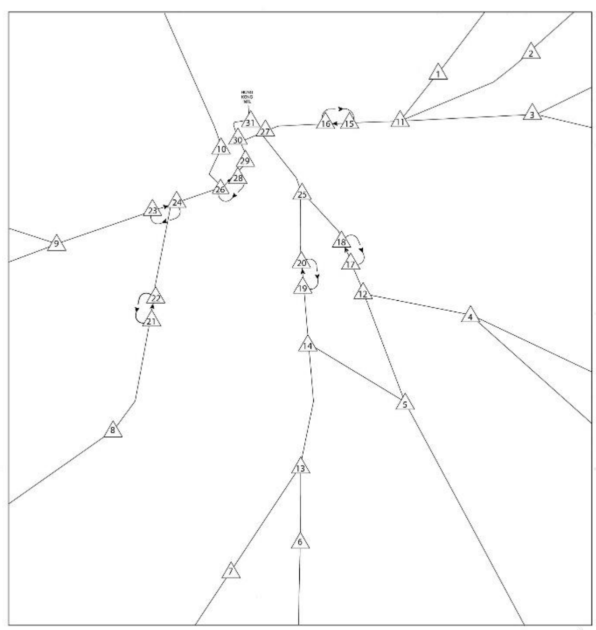

Figure 4. The air traffic route in the HKIA.

Fig 4 shows the normal air route network in the TMA. Since the length of each route is enough to deal with the conflict situation at the HKIA. A mono-aeronautical holding pattern is supposed to be imposed [11]. As a result, 10 arriving route and 26 alternative paths are modelled.

The number of flights per hour in HKIA is around 60. We determine the computational load when the number of flights is increased. The number of flights in the proposed instance is $I = 2, 4, 6, 8, 12, 14$. Therefore, using the exact method, the best computation time should be less than $CPU = 2, 4, 6, 8, 12, 14$ minutes correspondingly to hold the continuity of the decision horizon.

The computation was performed with the configuration of Intel Core I7 3.60GHz CPU and 16 GB random-access memory under the *Windows 7 Enterprise 64-bit* operating environment. The exact method is coded with C# language using *Microsoft Visual Studio 2017* and *IBM ILOG CPLEX optimisation Studio 12.8.0*.

TABLE II shows that computation time for the instance with $I = 2, 4, 6, 8$ is within a second, while the computation time for the instance with $I = 12$ takes approximate 2 minutes to compute an optimal schedule. However, when the number of flight being 14, the exact method cannot obtain the optimal result within one hour.

TABLE II. THE COMPUTATIONAL RESULTS

# flights	Upper bound	Lower bound	CPU (sec)	Condition
2	4751.56	4751.56	0:00:00.13	Optimal
4	5870.61	5870.61	0:00:00.16	Optimal
6	5236.55	5236.55	0:00:25.52	Optimal
8	7239.42	7239.42	0:00:28.81	Optimal
12	7753.87	7753.87	0:02:03.41	Optimal
14	8090.18	6596.67	1:00:00.00	Near-optimal

IV. CONCLUSION

This paper proposes a novel alternative path approach for TTFP. The model considers the path coordination approach and aeronautical holding method to develop a TTFP schedule with the support of the computational intelligence. Decision makers may rely on computational intelligence to handle flight path selection and holding decision, achieving less ATC manual effort on control flight schedule and reducing ATC workload. Furthermore, the conflict detection will also help the ATC to determine the best approach route with zero conflict, as well as minimise the overall completion time of a schedule.

Future research is recommended in the following aspects. First, the computation time for large size instance is increased significantly, meta-heuristics or decomposition approaches may be able to reduce the computation time for practical usage. Second, the parameters uncertainty may also be integrated into the model to develop stochastic or robust models in hedging uncertainty.

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ACKNOWLEDGMENT

The research was supported by the Hong Kong Polytechnic University, Hong Kong and Nanyang Technological University, Singapore. Our gratitude is also extended to the Research Committee and the Department of Industrial and Systems Engineering, the Hong Kong Polytechnic University for the support of this project (RU8H) and (G-UA4F). The authors would like to express their appreciation towards the Hong Kong International Airport and FlightGlobal for their assistance with the data collection.

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