Air Traffic Performance Improvement of Congested Terminal Airspace

with Genetic Algorithm Based Optimization

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Summary

With the increase of air traffic demand, the terminal airspace becomes more and more congested. Future air transport systems are expected to handle increasingly heavy demand on air traffic, especially in a highly constrained terminal airspace. Therefore, the realizable capacity of current terminal airspace is a challenge for future air transport development.

The objective of this thesis is to understand and identify the system vulnerability of congested terminal airspace, and then optimize aircraft landing sequence and runway allocation in order to maximize the TMA capacity and minimize delay. Thereby an algorithm for optimal arrival flight sequencing and runway assignment in a terminal airspace has been proposed.

In this project, the optimization scheme selected to tackle this problem is genetic algorithm. Genetic algorithm is a problem solving system based on principles of evolution and heredity. It consists of an iterative procedure to identify and preserve the candidate solutions with higher fitness, as well as generating new possible candidates through chromosome operations. After a reasonable time of iteration, a feasible optimal solution will be generated. As demonstrated in this thesis, genetic algorithm is well adapted for resolving the congestion of terminal air traffic.

The outcome of this optimization scheme is only the assignment of each aircraft with a respective landing time and runway, however it does not provide instructions on how aircraft can achieve this in real-world actions. Although the separation limits are in force for the initial positing and landing sequence of aircraft, there exist a risk that the separation limit may be violated during the periods in between. Therefore this is one of the major motivations to design a simulation scheme and incorporate speed adjustment and holding within it. In daily operations, altering the airspeed is a common tool that air traffic controllers used to achieve the desired arriving time of the aircraft. Hence, it is considered as the primary means of aircraft adjustment in the simulation.

To visualize the optimization result and adapt for realistic situations, a dynamic simulation was designed. The fundamental logic of the dynamic simulation is to incorporate a quick optimization scheme into the simulation loop. As a result, the computational performance will be significantly improved; bring it closer to be implemented in the real world air traffic control dynamic environment.

In this thesis, the proposed optimization scheme and simulation design is validated by using the arrival routes of Hong Kong International Airport. Accordingly, the genetic algorithm based optimization design is capable of generating a rather optimum landing sequence and runway allocation with minimal computation time. Therefore, the proposed scheme may be implemented into the real world air traffic control procedure to fill the void left in strategic decision making during high workload periods. This is not only crucial to efficient air traffic management, but also a cost effective solution to deal with the increasing flight demands.

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Abbreviations

ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
CAP	Collaborative Arrival Planner
CPS	Constrained Position Shifting
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FCFS	First Come First Served
GA	Genetic Algorithm
IAP	Instrument Approach
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
TA	Time Advance algorithm
TMA	Terminal Airspace
VHHH	The ICAO sign for Hong Kong International Airport
VOR	VHF Omni Directional Radio Range

Symbols (Greek)

$\Delta_{i-1,i}$	Minimum separation distance between one aircraft and the preceding one

Symbols (Roman)

E_i	Estimated arrival time of i^th aircraft
f_{st}	Fraction of the population to be renewed
N_g	Maximum number of generation
NP	Number of planes
P_c	Crossover probability
P_m	Mutation probability
q	Population size
S_i	Scheduled arrival time of i^th aircraft
$S_{toLIMES,evious}$	The distance to reach LIMES waypoint for the previous aircraft in arrival sequence
$S_{toLIMES}$	The distance to reach LIMES waypoint
$t_{opt,result}$	The landing time given by the optimization result
$t_{scheduled}$	The scheduled arrival time
t_{step}	The time step in simulation

V_{GS}	The ground speed
V_{normal}	The normal airspeed value
V_{target}	The target airspeed

Chapter 1

Introduction

1-1 Background Information

As the demand for flight is continuously increasing over the world, limited capacity resources in the terminal airspace are currently under strain. However, construction of additional runways and airport terminals might not always be feasible or economically efficient. Therefore, smoothing air traffic congestion of terminal airspace based on the existing airport facilities has become crucial to efficient air traffic management.

Previous researches show that air traffic assignment techniques have been developed in a way to spread the traffic demand in time and space, due to the fact that congestion is related with aircraft located at the same place during the same period of time [1]. However, this technique induces the modification of flight plans, which in return will significantly increase the air traffic controller workload. Therefore the objective of this thesis is to identify and understand characteristics of congested terminal airspace, and then to develop an optimization scheme to improve the performance of the congested terminal air traffic, while maintaining the ATC efficiency and aircraft safety.

1-2 Research Question and Hypothesis

The main research question can be formulated in such way that:

How to develop an optimization scheme to improve the performance of the congested terminal air traffic?

In order to answer this question, it is natural to start the research with finding the system characteristics. Hence, one of the sub-question will be:

How to identify and understand the system characteristics of congested terminal airspace?

The hypothesis is that human factor plays a very important role in the scheduling and guidance procedure in current air traffic system. However, this procedure is empirical: experience based and usually not optimized. Therefore, the other sub-question can be stated as:

How to develop an optimized logistic for air traffic controller's flight scheduling and guidance procedures?

1-3 Organization of the Thesis

This report will be organized as follows: First, in chapter 1, an introduction, which provides a background of the research field, and research questions raised by this study, as well as the basic methodology to the research questions of the thesis, will be presented. Chapter 2 will provide a literature review with respect to the theoretical background on improvement of congestion terminal airspace; this chapter contains the basic knowledge needed to understand the development of ATC in congested terminal airspace.

In chapter 3, the fundamental optimization algorithm will be selected, and the reason for choosing this scheme will be also explained. In chapter 4, a detail of the optimization algorithm is given. This provides information on which calculations are used within this thesis and how they are applied. Chapter 5 will discuss the selection of airport and scenarios for the optimization scheme and simulation design. To visualize the optimization result and adapt for realistic situations, a direct simulation and dynamic simulation will be introduced in chapter 6.

Then chapter 7 presents the subsequent results, and the effect of dynamic simulation will be analysed. Finally, chapter 8 will give the conclusion and recommendation to this thesis.

Part I

Research Background and Description

Chapter 2

Literature Review

2-1 Introduction

In this chapter, several aircraft landing optimization algorithms in previous studies will be illustrated. The main principle of those techniques is to create the optimal landing sequence and schedule. As the first step, the potential for such technique to achieve higher terminal airspace (TMA) capacity will be evaluated. Furthermore, throughout these literature reviews, it is intended to find an appropriate optimization approach which will be able to reduce the terminal airspace congestion without adversely effecting on the air traffic controllers' workload.

2-2 Background Information

As the demand for flight is continuously increasing globally, limited capacity resources in the terminal airspace are currently under stress. A major effect of this air traffic growth has been the increasing of flight delays and the associated cost. In a recent study, approximately 22% of all flights in the United States were delayed on arrival, 20% on departure, and 3% were cancelled [2]. The economic consequences of these delays, together with the associated inefficiencies, was estimated to result in additional $31.2 billion operating costs in the U.S. in 2007 [3]. In Europe, the average air traffic flow management (ATFM) delays has reached 75620 minutes per day, and the ATFM delay per flight is 2.9 minutes on average for all flights by 2013 [4]. It has been estimated by the FAA that, in the foreseeable future, if the air traffic control (ATC) infrastructure and operating procedure does not change, there could be an aviation accident once every seven to ten days [5].

The reasons for causing those delays are complex. For instance, airport resource is one of the major driven factors of delay of some airports in the developed regions, where the airports are operating at or even beyond the designed capacity limits during the peak hours.

Another crucial factor for causing the delay is due to constrain of airspace resource. It is noted that in 1970's, Europe, U.S., and other developed areas began to show signs of congestion, but the industry generally does not expect that the lack of airspace resources would quickly turn out to be the bottleneck of the system. With the rapid growth of civil aviation transportation in recent years, terminal area congestion problem has spread to other areas. Now, it is widely recongonized that the issue of terminal airspace congestion is severe and the traffic flow of terminal airspace has already become the bottleneck of the whole traffic flow [6].

Hence, it is of great importance for improving ATC strategies at over-saturated airports. Air traffic controllers should make full use of aircraft performance characteristics to increase the amount of flight movements per unit time of the airport runway. This effectively expands the airport capacity while ensuring the save operation of the aircraft.

Moreover, to regulate air traffic efficiently and safely (e.g. optimizing aircraft landing sequence and runway assignment during approaching), decision support tool must be developed and provided to air traffic controllers to reduce the their workload and decrease the working complexity.

Previous research shows that modification of arrival slot allocation is the most common way to avoid congestion in the terminal area of airport[1]. This methodology is based on the conventional first come first served (FCFS) algorithm. It rearranges the arrival sequences according to the estimated time of arrival of the aircraft [4]. However, the implementation of this methodology requires air traffic controller with abundant experience, and accordingly increases the controller workload. Hence in this chapter several advanced scheduling and sequencing algorithms will be illustrated in order to find out the current system vulnerability of congested terminal airspace.

2-3 State of Art/Literature Review

To relieve the congestion, one of the solutions is to construct new runway and upgrade the airport facilities. However, as this might not always be feasible or economically efficient, this master thesis will focus on the development and evaluation of comprehensive dynamic scheduling algorithms for the congested terminal airspace.

Terminal airspace is a transition section of airspace, which connects the en-route flight and departure or arrival flight, and attribute to most of delay of the flights [4]. The reason for that is because terminal airspace system is a highly complicated environment, in which different static and dynamic elements are involved. Particularly, these uncertainties would have become more significant when a sector has high levels of traffic, which as a result, make the workload of terminal airspace traffic controller unpredictable [7]. To identify the terminal airspace vulnerability, first we need to understand the structure of terminal airspace.

2-3-1 Terminal Airspace Structure

As flights are descending and climbing to and from the airport, actual airspaces often take the shape of an upside-down wedding cake, as shown in figure 2-1. This upside-down wedding cake is divided into a control zone and terminal control area, which is handled by the airport tower and area controllers, respectively.

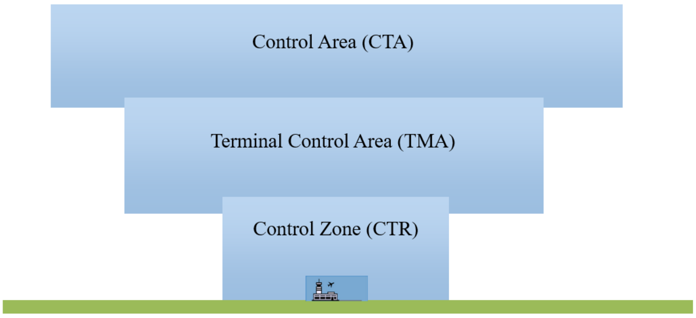


Figure 2-1: A schematic overview of a generic terminal airspace

Terminal airspace governs the aircraft flying in proximity to an airport up to a certain altitude, with the purpose of connecting the airport to the upper air route network, through the TMA exit and entry points. Specific routes are published for this airspace, called Standard Instrument Departures (SIDs) or Standard Terminal Arrival Routes (STARs).

SID procedures are predefined route profiles for departing traffic to strictly follow to ensure safety as well as to fulfil noise abatement requirments over inhabited areas. Whereas the STAR is a published procedure followed by aircraft on an instrument flight rules (IFR) flight plan for approaching the destination airport [8].

A typical STAR consists of *a set of starting points, called transitions, and a description of routes (typically via VORs and intersections) from each of these transitions to a point near a destination airport, upon reaching which the aircraft can join an instrument approach (IAP) or be vectored for a final approach by terminal air traffic control* [9]. A sample of STAR of Hong Kong International airport is shown in figure A-1. Different runways in the same airport could share a single STAR; in this case, aircraft follow the same arrival route up until reaching a final waypoint, after which they continue to follow the approach procedures for their respective landing runways [10].

To achieve optimal spacing, aircraft are generally guided along a STAR, until the controller clears them directly to the final approach fix. In this way the controller is able to space the aircraft onto the final approach. As such, STARs are designed to enable the controller to adjust the flight trajectory when required.

2-3-2 Capacity of Terminal Airspace

In order to improve the performance of congested terminal airspace, it is also crucial importance to understand and identify the capacity of terminal airspace. According to the definition in FAA, the traffic density in operational hour is a function of the position and velocity of all aircraft in a sector [9]. Based on the experience in Europe, Majumdar *et al* [11] suggests that the capacity of terminal airspace in an ATC sector is largely determined by air traffic controllers' workload. Therefore the capacity of terminal airspace can be defined as

The maximum number of aircraft that are controlled in a particular ATC sector in a specified period, while still permitting an acceptable level of controller workload. [12]

In most optimization algorithms, it turns up to be that capacity of TMA is one of the most crucial constraints in building mathematical models. Therefore, it is developed as a part of this thesis to evaluate the capacity of terminal airspace, in order to improve the air traffic of congested TMA. To evaluate the performance of TMA, the so called operating curve in which average scheduling delay is plotted versus throughput is introduced. As illustrated by a vertical dashed line in figure 2-2, the maximum throughput for each of these curves is called the capacity [13]. As specified by the operating curve, a choice of desired throughput results in a corresponding average delay.

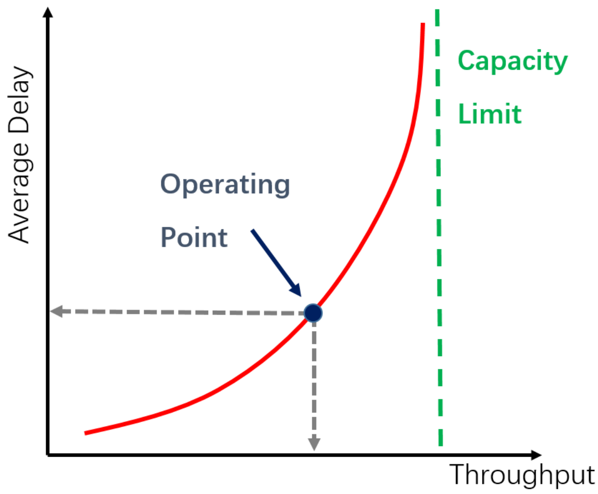


Figure 2-2: Operating curve

2-3-3 Factors Affecting Terminal Airspace

Research indicates that the capacity of terminal airspace is affected by the complex interaction of number of parameters, which including the situation in the airspace, the state of equipment, and also the state of controller. These parameters are considered as the drivers of controller workload, and consequently the driver of terminal airspace throughput [14]. Therefore the effect of these parameters on congested terminal airspace, as well as on controller workload, must be understood if appropriate strategies for increasing airspace capacity are to be applied. In the following paragraphs, the driving factors affects the capacity of terminal airspace will be elaborated.

First, the airport terminal airspace capacity is determined by its associated runway system factors. The number of the runway, their length and layout, will largely determine the capacity of the airport terminal airspace at any given period of time. Among them, the runway layout also depends on many factors, including the local terrain and the main direction of wind. In this regard, the runway is the primary bottleneck in the terminal airspace control system [15].

Secondly, the characteristics difference of the aircraft will also affect the capacity of the runways system. *Lower performance aircraft determine airspace capacity by constraining the performances of other aircraft within the system* [16]. Since various types and sizes of aircraft are designed for different missions, this performance difference can not be eliminated thus must be accounted by the design of efficient ATC systems.

In addition, aircraft wake vortexes is another issue related to aircraft performance characteristics. When aircraft pass through the air, coherent energetic air will be generated on the wakes. In order to prevent accidents caused by wake vortexes, separation standards have been established by ICAO, see table 2-1 to table 2-4 [17].

However, the current wake vortexes standards were established in the 1970s, back to that period, knowledge to wake vortexes was quite limited and conservative. Thanks to the technology development, a concept of dynamic wake vortexes separation was introduced [18]. This concept suggests that the total of wake vortex separations can be reduced by optimizing an airport traffic pattern through runway allocation and aircraft sequencing. It is this concept paves a way for the further research of this thesis.

Table 2-1: Minimum Arrival Separations - Visual Flight Rules (Nautical Miles)

Lead \ Trail	**Small (S)**	**Large (L)**	**Heavy (H)**
Small (S)	1.9	1.9	1.9
Large (L)	2.7	1.9	1.9
Heavy (H)	4.5	3.6	2.7

Table 2-2: Minimum Arrival Separations - Instrument Flight Rules (Nautical Miles)

Lead \ Trail	**Small (S)**	**Large (L)**	**Heavy (H)**
Small (S)	3	3	3
Large (L)	4	3	3
Heavy (H)	6	5	4

Table 2-3: Minimum Departure Separations - Visual Flight Rules (Seconds)

Lead \ Trail	**Small (S)**	**Large (L)**	**Heavy (H)**
Small (S)	35	45	50
Large (L)	50	60	60
Heavy (H)	120	120	90

Table 2-4: Minimum Departure Separations - Instrument Flight Rules (Seconds)

Lead \ Trail	**Small (S)**	**Large (L)**	**Heavy (H)**
Small (S)	60	60	60
Large (L)	60	60	60
Heavy (H)	120	120	90

2-4 Development of Algorithms for Improving the Capacity of Terminal Airspace

Terminal airspace aircraft sequencing methods aim at optimizing the landing time of all aircraft to resolve traffic congestion, while maintaining the minimum separation requirements. Typical methods commonly used globally are the first come first serve (FCFS) method. It is based on sequencing incoming aircraft according to their estimated time of arrival (ETA). However, since aircraft usually have different characteristics, especially with heavy jet and their additional separation requirement, more efficient sequencing scheme might exist in comparison to the FCFS method [15].

To improve the terminal airspace control system, and give air traffic controller a better idea of the degree of congestion, industry began to analyse the theory of air traffic flow management since the middle of 1980's.

In 1989, R.G. Dear proposed a so called Constrained Position Shifting (CPS) [15], a methodology for sequencing and scheduling aircraft in high density of terminal area. *Basically, no aircraft will be assigned to land more than a pre-specified number of positions from its initial FCFS position.* This methodology has been demonstrated via fast-time simulation, to be substantially better than FCFS methodology.

Another alternative to meet the observed and forecast growth in traffic demand is the practice of Time Advance (TA) algorithm [19]. The fundamental principle of this scheduling algorithm is to speeding up an aircraft toward a scheduled location without modifying the original sequence. Time advance has a potential capability to minimize the excess separation and thereby to increase the throughput of the arriving traffic. However, a cost associated with time advance is the fuel expenditure when an aircraft was assigned to speed up. In addition, all arrival times will be changed due to the implementation of time advance algorithm; this will certainly increase workload of air traffic controller.

Because of the dynamic nature of air traffic control, an algorithm called Implicit Enumeration [20], has been developed to operate in a dynamic feedback environment. This algorithm indicated for many multi-runway airports, delay can be reduced when both runway assignment and aircraft sequencing are considered simultaneously.

While above mentioned methodologies provide valuable information regarding the tendency of air traffic flow management, caution needs to be exercised as the number of aircraft increased. The congestion problem can be solved reasonably while the number of aircraft is relatively small. However, these methodologies took relative long time to solve complex problem while more variables are involved. Heuristic methods commonly are used to search for such solution. Nevertheless, at the very beginning phase of this research, people only concerned with the issue of assigning landing times to incoming aircraft, and ignoring the case of multi-runway airports where runway assignment is also required. [21].

In the last decades, other more advanced optimization approaches has been developed by scholars worldwide; including the Optimization-Based Analysis of Collaborative Airport

Arrival Planning, which was a method to analysis of the Collaborative Arrival Planner (CAP), a concept under development by NASA as decision support tool for improving air traffic management [22].

Moreover, in 2008, another efficient scheduling algorithm was proposed by Aditya, in which combinatorial optimization techniques was used to find the optimal arrival aircraft sequence and the optimal STAs for the aircraft at a certain reference point [23]. However, in the proposed algorithm still no consideration had been given to optimal runway assignment. Nevertheless, the researcher emphasized that in scenarios where the category of aircraft flows on these routes are mixed, assigning aircraft to land on alternate runways could help increasing the capacity of the airport [23].

With association of the development of terminal airspace control theory, a number of autonomous aircraft sequencing systems have been developed for arrival management as well. In the US, the authority recently realized that without reliable and accurate information on the severity of forecast congestion, controllers may not be able to respond with the most efficient aircraft landing sequence [24]. Thus, the Federal Aviation Administration (FAA) is dedicated to managing congestion and reducing delays by implementing the Next Generation Air Transportation System (NextGen). One of the major goals of NextGen is *to develop a decision support tool to predict congestion in the airspace and find ways to display forecasted problems to air traffic controllers* so controllers can more accurately schedule aircraft in the terminal airspace [24].

In Europe, focus had being shifted to how to design the terminal airspace in such way that the capacity of the airspace can be maximized. A number of ground constraints needs to be taken into account for terminal airspace design, such as terrain profiles and noise-sensitive neighbourhoods. Curved approaches [25] and other techniques are developed in order to smooth air traffic flow in such scenarios. However, when a design has been made, the continuous changes in these sectors and other variables will eventually turn the original construction inefficient, making it necessary to redesign the airspace.

All the above reviewed works have proven that TMA is a complicated system, which affected by the complex interaction of number of parameters. Moreover, it is found that there is no existing mathematical model which can directly be implemented into the congested TMA environment. In such situation, it is of importance to find a good feasible solution that is reasonably close to being optimal, while it should also be sufficiently efficient to deal with such large problem.

2-5 Introduction to Heuristic Algorithms

In the current air traffic control system, aircraft movements is manuvoured by air traffic controllers along a series of standard trajectory segments toward the airport [26]. Modification of slot allocation is the most common algorithm to deal with the terminal airspace congestion. Referring to the previous findings, significant improvement can be obtained while runway assignment has been added to the optimization model. Thereby, it is naturally to draw a hypothesis, such that, if we can optimize the capacity of TMA by considering the aircraft sequencing and runway assignment simultaneously, more accurate schedules can be obtained.

Considering TMA optimization problem is a complex problem, conventional algorithms have been proven to be inefficient for addressing such problems. A heuristic method is likely a promising idea for identifying solution for tackling large and complex problems. This procedure is often consisted with *iterative algorithm, where each iteration involves conducting a search for a new solution that might be better than the best solution found previously. After a reasonable time of iteration, a feasible optimal solution will be generated* [27].

The famous no-free-lunch theorem states that without a prior knowledge of the mathematical problem, it is not possible to predict or to compare the performance of different optimization methods. It can be difficult, if not impossible, to fully describe the runway assignment problem by an mathematical model. Therefore the use of heuristic methods, which have advantages *in dealing with multi-dimensional, non-differential, non-continuous, and even non-parametrical problems* [1], is considered preferable for this particular application.

2-6 Summary and Conclusions

Throughout the previous reviews, we found out that, although aviation industry and academic world have been aware of the potential problem of congested terminal airspace for many years, a state of art of the existing methodologies show that this problem is still partially treated and the optimal solution has not been determined due to the complexity induced. This not only creates challenges for collecting relevant papers for literature review, but also makes it difficult to stay objective in comparing different methods.

To determine the system vulnerability in a congested TMA, it has been started with identifying the major influencing factors of the terminal airspace traffic. It is found that when the terminal airspace traffic demand approaches or exceeds its capacity, it will result in congestion. The terminal airspace capacity depends on many factors, such as the number of runways available, aircraft performance characteristics, wake vortex turbulence, ATC equipment and procedures, and current or anticipated weather.

To resolve the terminal airspace congestion, most of previous related works were primary focusing on spreading the traffic demand in time and space [28]. However, this technique requires modification of flight plans manually, which in return will significantly increase the air traffic controller workload.

Referring to the previous findings, Runway assignment algorithm can increase the terminal airspace throughput and reduce delay without adversely affecting controller workload.

These findings pave the way for comprehensive approach to the worst terminal airspace congestion scenario.

In addition, the outcomes of previous research using optimal control were not guaranteed to be global optimal solutions. On the other hand, the outcomes of research using heuristic method could theoretically provide global optimal solutions. However, the computational time of heuristic programming in previous research may rise significantly when the number of aircraft increases. Therefore, in the following chapters, it will aim to develop an optimization tool for the air traffic controller to improve the TMA performance by considering the aircraft sequencing and runway assignment simultaneously and to obtain a near-optimal solution within an acceptable computational time.

Chapter 3

Research Descriptions

3-1 Introduction

The objective of this research is to identify and understand the system characteristics of congested terminal airspace, and then to develop a integrated optimization scheme to improve the performance of the congested terminal air traffic. In this chapter, the fundamental optimization method will be selected, and the reason for choosing the genetic algorithm will be briefly explained.

3-2 Selection of Methods

The nature of this research question is an optimization problem; thus selecting an optimization method is essential in resolving the problem at hand. Nevertheless, the wide variety of categories of optimization algorithms poses challenges in how to select the most suitable one.

In dealing with simple models that have little number of constrains, some linear/nonlinear programming methods are proven to be effective and efficient in finding the optimal solution. However, with the complexity of the practical problem increases, the difficulty of forming the models correctly and solving the problem efficiently also rises dramatically.

Since the main focus of this research is not really to generate obviously improved results in much idealized situations; but rather to provide a useful platform that is capable of incorporating various factors that may occur practical operations. This means that instead of searching for the guaranteed global optimum in simple ideal models; it is more favourable to select a heuristic method that is able to discover a good feasible solution in situations with added complications.

Tabu search, simulated annealing and genetic algorithm are all examples of metaheuristics for finding a good feasible solution that is reasonably close to the optimum. Tabu search and simulated annealing focus on moving from a single trial solution to a neighbouring trial solution with improved results, while occasionally allowing non-improving moves to exit local optimums and enlarge search areas.

Another approach is by using Genetic Algorithm idea, which mimics the process of natural selection. This method is based on the analogy to the biological theory of evolution, works with multiple trial solutions simultaneously. Based on the concept of survival of the fittest, unfavourable trial solutions are discarded and being replaced by new ones, while promising trial solutions are retained and can pass on some of their characteristics to the new trial solutions.

This scheme of optimization brings various benefits and advantages for solving this particular problem of aircraft arrival, thus genetic algorithm is selected as the main optimization scheme for this project. The following items are some detailed considerations contributing to this choice.

- **Simultaneous optimization for aircraft sequencing and runway assignment**
  Air traffic controllers at major airport hubs are facing many challenges. Besides the towering amount of traffic volume to be handled, one of the major difficulties is also the amount of choices of approach routes and landing runways that are available and must be determined for each incoming aircraft. Genetic algorithm offers a very intuitive solution that relief the air traffic controllers by offering them with an optimum combination together.

- **Flexible optimization**
  Although genetic algorithm does not scale well with increase in problem complexity, it has a very flexible choice of setting parameters that can quickly adapt from a lengthy optimization scheme focusing on precision into a quick method prioritizing on efficiency. This generates more possibility for the way the optimization scheme can be integrated into an existing system.

- **Relative Simple Mathematical Model**
  The genetic algorithm replicates the natural selection process which is intuitive to understand, and it only requires relatively simple mathematical models to formulate the problem. This is reconfirmed in chapter 4 where the optimization scheme is established with mathematically simple objective functions and intuitive choices for the chromosomes.

- **A multi-point search for optimum**
  Genetic algorithm is a process that searches the optimum solution with an initial population formed by many individuals. Therefore, it can be considered as a multi-point search which is more efficient.

Part II

Optimization and Simulations

Chapter 4

Optimization Scheme

4-1 Introduction

With the decision to use the genetic algorithm for the optimization, one must analyse the characteristics of the problem to be resolved to create a suitable calculation scheme. In this chapter, how the genetic algorithm (GA) based optimization scheme is developed will be elaborated. The design of such a scheme is demonstrate in section 4-2 and the determination of relevant parameters is discussed in section 4-4.

4-2 Scheme Design

To simplify this algorithm, a two-runway airport will be taken as example. A proposed optimization algorithm for this problem is genetic algorithm. Genetic algorithm is a problem solving system based on principles of evolution and heredity [1]. It consists of an iterative procedure to identify and preserve the candidate solutions with higher fitness, as well as generating new possible candidates through chromosome operations.

Figure 4-1 illustrates the flow chart summarizing the tasks to be taken for the genetic algorithm powered aircraft arrival optimization.

4-2-1 Set Optimization Parameters

For the genetic algorithm, typical settings parameters include number of parameters (NP, a.k.a. number of planes), crossover probability (P_c), mutation probability (P_m), the fraction of the population to be renewed (f_{st}), population size (q) and maximum number of generations (N_g). Determinations of the values for these items are discussed in section 4-4.

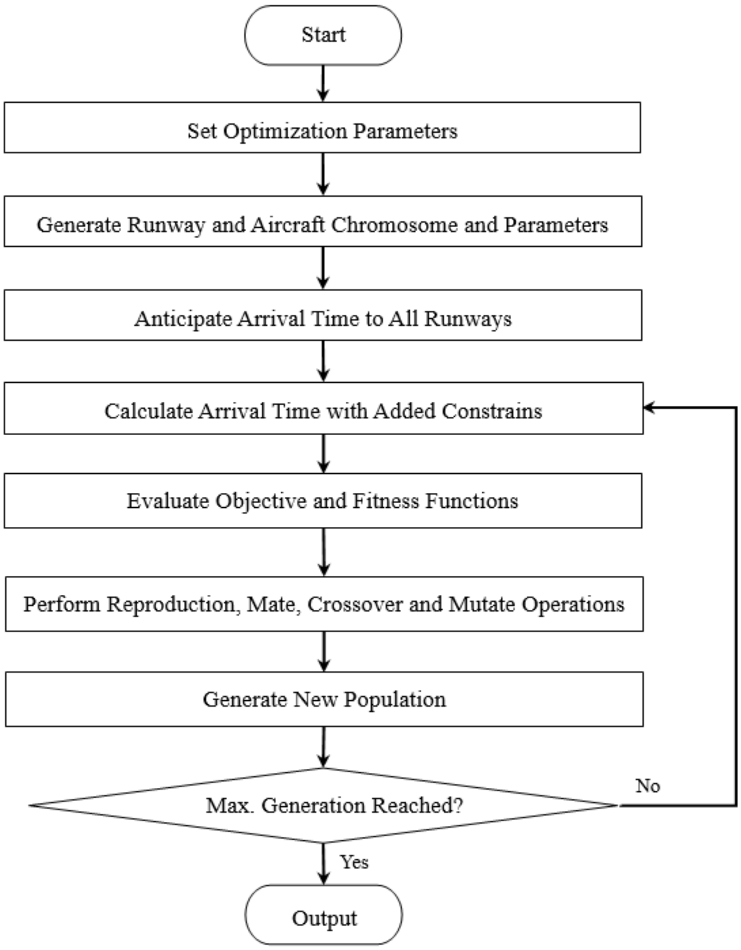


Figure 4-1: Flow chart of the genetic algorithm based optimization scheme

4-2-2 Generate Chromosome and Parameters

In this initialization process, the aircraft and runway chromosome is generated together with aircraft type and location parameters. For the scenario designed and simulation design, additional parameters such as aircraft arrival direction and flight identification information (see section 5-3 and 6-5) also need to be defined at this stage.

Chromosome

For the genetic algorithm, a set of chromosome must be defined representing the real world counterparts. In this particular case, the focus of the scheme is to yield the optimum sequence for aircraft landing line-up, and the corresponding runway assignment that would realize this result. Therefore, one chromosome set would include these two items. The following is one example:

Aircraft chromosome: [6 2 3 0 9 1 5 7 4 8]
Runway chromosome: [2 1 2 2 2 1 1 2 1 2]

Aircraft type

Due to the potential danger of wake turbulence encounter, aircraft of difference size categories must follow strictly the restrictions of minimum separation. For higher altitude flights, this minimum is defined by the distance (normally 3 nautical miles) between the two aircraft; whereas for the take-off and landing, a regulation in the form of minimum time applies. Thus, all aircraft are assigned with type identifiers generated randomly with "Small" representing single aisle aircraft (e.g. Boeing 737, Airbus 320 and regional jets), "Large" representing medium-sized wide-body aircraft (e.g. Airbus A330 and Boeing 787), and "Heavy" dedicated for jumbo jets.

Aircraft Location

The initial positions of the aircraft are generated by another random process that determines the distance of the aircraft from certain way-point along the air-routes. Here, special attention is paid to eliminate potential conflicts: adjacent aircraft within the separation limit will be eliminated and recreated elsewhere.

Based on the position of the aircraft, and according to specific flight routes and an airspeed reduction plan till the runway thread-hold, the minimum time needed for the aircraft to land at each runway can be determined. This matrix parameter is denoted as E and an example is demonstrated as equation 4-1

$$E = \begin{bmatrix} 2 & 14 & 6 & 6 & 12 & 32 & 9 & 3 & 5 & 7 \\ 3 & 16 & 8 & 10 & 8 & 36 & 6 & 4 & 2 & 9 \end{bmatrix} \tag{4-1}$$

Correlating this to the landing sequence and runway selection defined by the chromosomes, the constrain-free arrival time for aircraft in each combination can be determined.

4-2-3 Calculation of Arrival Time with Added Constrains

The arrival time for the preceding aircraft should not be earlier than that of the previous aircraft landing on the same runway plus a mandatory separation. This requirement could lead to potential delays in arrival especially in congested scenarios.

The expected actual arrival time incorporating this separation restriction is represented by the parameter S. For every aircraft, when its value of minimum time to land (E_i) is smaller than the landing time of previous aircraft on the same runway (S_{i-1}) plus the minimum time separation requirement, then the expected actual arrival time for that aircraft (S_i) will be equal that sum. Otherwise,it will be equal to the minimum time to land (E_i). In equation formulation, S_i could be expressed as [29]

$$S_i = max(S_{i-1} + \Delta_{i-1,i}, E_i) \tag{4-2}$$

The minimum time separation (Δ) between different types of lead and trail aircraft are illustrated in Table 4-1.

Table 4-1: Minimum time separation between aircraft in landing lineup (min)

Lead \ Trail	**Small (S)**	**Large (L)**	**Heavy (H)**
Small (S)	1	1.5	2
Large (L)	1	1.5	1.5
Heavy (H)	1	1	1

4-2-4 Evaluations

As above-mentioned, the earliest possible time for an aircraft with index i to land is the minimum value in each column of the E matrix ($E_{i,min}$). The difference between this and expected actual arrival time of that aircraft (S_i) can be considered as the delay of the arrival, which would be an optimum indicator for the performance of the optimization. Therefore, the sum of the delay time for all aircraft ($\sum(S_i - E_{i,min})$) is considered as the objective function of the genetic algorithm to be minimized. Thus the fitness function can be defined as

$$f = \frac{1}{1 + \sum(S_i - E_{i,min})} \tag{4-3}$$

4-3 Chromosomes Operations and New Generation Creation

For generation renewal, four operations are conducted on the chromosome sets, namely reproduce, mate, crossover and mutate. In the reproduce process, according to the fitness level, parents are selected to form the new generation. Then mate operation reorder the chromosomes in each set randomly. Crossovers are only operated on the runway chromosome: a section of chromosome series is interchanged with the numbers from another chromosome of the same type.

Before the operation:

Runway chromosome 1: [2 1 2 2 2 1 **1 2 1 2**]
Runway chromosome 2: [1 2 1 2 1 2 **2 2 2 1**]

After the operation:

Runway chromosome 1: [2 1 2 2 2 1 **2 2 2 1**]
Runway chromosome 2: [1 2 1 2 1 2 **1 2 1 2**]

Similarly, in the mutate operation, one element of an aircraft chromosome series is exchanged with another element of itself. Thus the uniqueness of aircraft identity number in the same chromosome can be guaranteed.

Before the operation:

Aircraft chromosome: [6 2 **3** 0 9 1 5 **7** 4 8]

After the operation:

Aircraft chromosome: [6 2 **7** 0 9 1 5 **3** 4 8]

4-3-1 Stopping Criteria and Result Output

Like many genetic algorithms applied in other fields, the maximum generation number (N_g) is used in this scheme as the stopping criteria of the optimization loop. The output of results is a list of aircraft ranked according to the arrival sequence. Items in the columns are the identification number of the aircraft, the type categories of the aircraft, the landing time, assigned runway for landing and the time of flight delay. One example is demonstrated in table 5-1.

4-4 Parameter Settings and Performance

4-4-1 Initial Settings

For genetic algorithm, determination of the settings parameters can be crucial to the precision and efficiency of the calculation scheme. Typically these parameters includes the crossover probability (P_c), mutation probability (P_m), the population renewal fraction (f_{st}), population size (q) and maximum number of generations (N_g).

These parameters are interdependent on each other; therefore, a starting value first has to be determined. From references, it is given that the typical choices for the population size is in the range between 20 and 1000; while for the crossover probability, commonly a value between 0.4 and 0.99 is preferable. The mutation probability is generally low, ranging from 0.0001 to 0.1. And for the maximum generation number, it may have a value between 100 and 500.

Based on these recommended choices, an initial setting has been empirically determined as the start of a trial and they are illustrated in table 4-2. Starting from this setting, a set of parameters for each one item will be generated according to the recommended range. Then independent optimization will run for 20 times for every value in the set. The eventual choice of the setting for the parameter will depends on the mean value as well as the variation for fitness in the 20 runs. Determination of the values for the maximum number of generations (N_g) will be discussed in section 7-2.

Table 4-2: Optimization initial trial settings

NP	q	P_c	P_m	f_{st}	N_g
15	64	0.5	0.1	0.4	300

Table 4-3 to 4-6 illustrate the average value in fitness and total delay for simulation with different settings. In the tables, the best resultant values are marked with bold font; and for the setting parameters to be determined, the eventual decision is set to bold.

4-4-2 Population Size

Population size (q) has a very direct influence on the performance and speed of the calculation, thus will be the first parameter to be determined. It can be observed in table 4-3 that with increase in population size, the average value for fitness seems to have a gradual rise. However, figure 4-2 has demonstrated that the variation in fitness has been significantly reduced for large population sizes, thus the best value achievable has actually reduced. Furthermore, considering the high sensitivity of calculation speed with regard to population size, a moderate value of 128 has been selected for the population size.

Table 4-3: Optimization results (mean value) with different population size (NP=15, P_c=0.5, P_m=0.1, f_{st}=0.4, N_g=300)

Population Size	32	64	**128**	256	512	1024
Fitness	0.148	0.215	0.259	0.276	0.273	**0.286**
Total Delay(min)	6.80	3.85	2.96	2.74	2.74	**2.52**

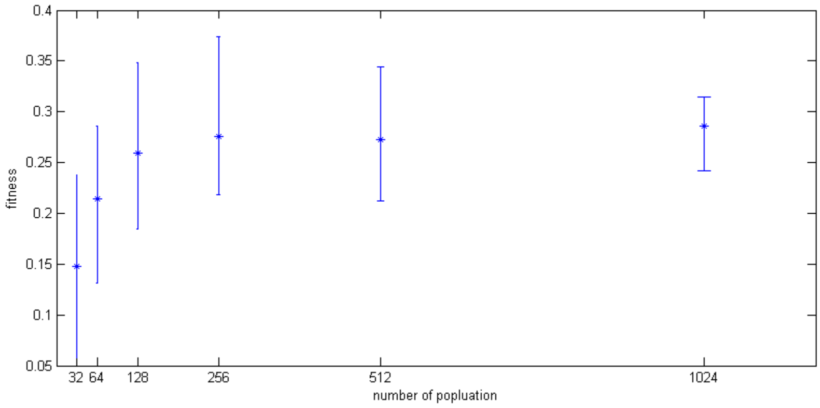


Figure 4-2: Variation in fitness for different number of populations in 20 independent runs

(NP=15, P_c=0.5, P_m=0.1, f_{st}=0.4, N_g=300)

4-4-3 Crossover Probability

Table 4-4 and figure 4-3 illustrate the optimization results with different values of crossover probability (P_c). It can be observed that the sensitivity is not very significant with all results showing similar mean values and value variations. The value of 0.7 shows a slight edge therefore being selected as the standard setting.

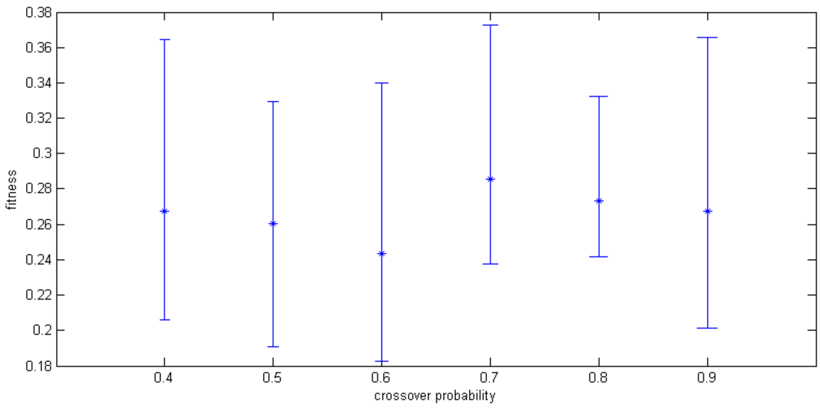


Figure 4-3: Variation in fitness for different crossover possibility in 20 independent runs

(NP=15, q=128, P_m=0.1, f_{st}=0.4, N_g=300)

Table 4-4: Optimization results (mean value) with different crossover probability (NP=15, q=128, P_m=0.1, f_{st}=0.4, N_g=300)

P_c	0.4	0.5	0.6	**0.7**	0.8	0.9
Fitness	0.267	0.260	0.243	**0.286**	0.273	0.268
Total Delay(min)	2.83	2.91	3.27	**2.58**	2.69	2.82

4-4-4 Mutation Probability

By contrast, the disparity in results with different mutation probability (P_m) values can be clearly identified. With increase in mutation probability, not only the mean value of fitness shows a considerable increase; the variation ranges and the highest fitness value achievable also get enlarged. Therefore the decision is rather straight forward to choose a value of 0.1 for the mutation probability.

Table 4-5: Optimization results (mean value) with different mutation probability (NP=15, q=128, P_c=0.7, f_{st}=0.4, N_g=300)

P_m	0.0001	0.001	0.01	**0.1**
Fitness	0.031	0.033	0.094	**0.269**
Total Delay(min)	31.59	29.92	10.88	**2.87**

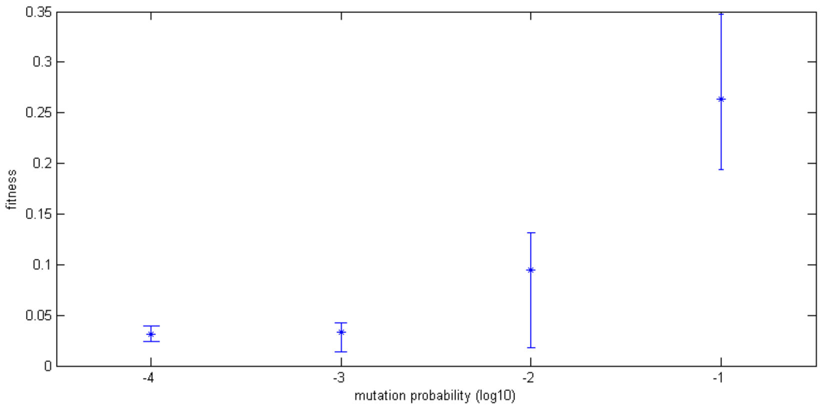


Figure 4-4: Variation in fitness for different mutation probability in 20 independent runs

(NP=15, q=128, P_c=0.7, f_{st}=0.4, N_g=300)

4-4-5 Population Renewal Fraction

For the fraction of the population to be renewed in every next generation (f_{st}), a gradual increase can be initially observed in table 4-6 and figure 4-5. Then the rise peaked and start to descend. Consequently, the fraction value of 0.6 which corresponds to the peak is selected for the renewal fraction.

Table 4-6: Optimization results (mean value) with different population renewal fraction (NP=15, q=128, P_c=0.7, P_m=0.1, N_g=300)

f_{st}	0.2	0.3	0.4	0.5	**0.6**	0.7
Fitness	0.194	0.251	0.262	0.269	**0.271**	0.267
Total Delay(min)	4.77	3.07	2.88	2.79	**2.78**	2.81

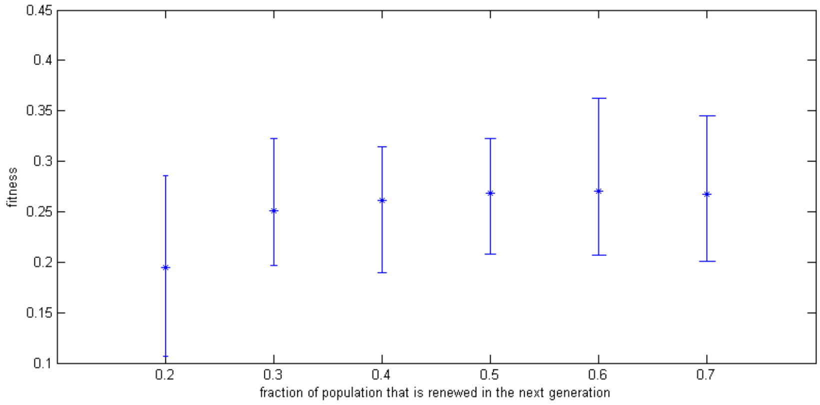


Figure 4-5: Variation in fitness for different population renewal fraction in 20 independent runs

(NP=15, q=128, P_c=0.7, P_m=0.1, N_g=300)

4-4-6 Determined Standard Values

The determined values for standard optimization parameter settings are listed in table 4-7.

Table 4-7: Determined optimization settings

NP	q	P_c	P_m	f_{st}	N_g
15	128	0.7	0.1	0.6	300

Chapter 5

Scenario

5-1 Introduction

This chapter starts with a detailed discussion on the selection of airport and scenarios for the subsequent optimization and simulation design (section 5-2). Then in section 5-3, the airways, navigation way-points and standard terminal arrival routes of the selected Hong Kong International Airport are illustrated. Section 5-4 briefly demonstrates the generation of aircraft for the scenario. Then the optimization scheme is adapted with the scenario to generate optimization results. These results are analyzed and verified in section 5-5. This is followed by section 5-6 with the elaboration on relevant assumptions and limitations of the scheme.

5-2 Choice of Scenario

It is determined that the proposed optimization scheme best suits the need of many two-runway equipped airports. Single runway airfields does not have the complication to assign incoming aircraft to a particular runway out of several choices. The need for such a scheme for huge aviation hubs with more than 2 runways is also low. Normally either have standard instrument arrival routes (STAR) with minimum conflicts that can be operated rather independently, or the traffic volume of the airport is limited by the congestion of airspace surrounding the airport rather than the runway itself.

Among many double runway airports, Hong Kong International Airport (ICAO: VHHH; figure 5-1) is very representative. The hills in the surroundings and Chinese airspace restrictions means that most aircraft landing on Runway 07L and 07R have to circle to its southeast, then fly west bound reaching LIMES, turn to the northwest before lining up the runway for the final approach (see appendix A). Quite a number of air route sections are shared by many different STARs, causing conflicts for independent runway operations.

As the result, for landing from the west side, Runway 07L is mostly used solely for landing and 07R for take-off. This is fine for off-peak operations; however, the strong base of a single airline (Cathay Pacific) contributes to a vast number of transfer passengers, leading to distinctive peaks in arrival and departure traffic. Therefore, an arrival peak with two runways in operation has been selected as the scenario to testify how big are the advantages can the optimization scheme offer.

Figure 5-1: Hong Kong airport with mountains in the surroundings

5-3 STAR and NAV Aids of VHHH Airport

It is assumed that for the simulation, all aircraft arriving from north (with heading smaller than 135 or larger than 270) will go via waypoint ABBEY; whereas aircraft from southwest (with heading between 135 and 180) will fly through CANTO; and BETTY will be used for aircraft arriving from the south-east (with heading between 180 and 270). The resultant classification is illustrated by figure 5-2.

From figure A-2 to A-4, it can be determined that the flight parameters (altitude and airspeed) defined at way-point CANTO is similar to the constrain imposed on way-point MUSEL for ABBEY arrival and way-point MANGO for BETTY arrival. Therefore, theses way-points are considered as the airspace boundary for the optimization scheme to be applied on. It is assumed that aircraft at these points had just decent to 10000 *ft*, thus having an airspeed of 250 *knots*. Figure 5-3 illustrates the arrival routes and navigation aids used in the simulation scenario, which composed the STARs from different arrival directions and landing on two different runways.

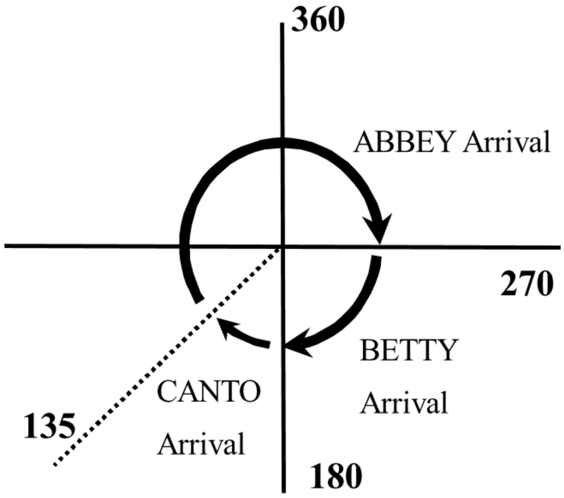


Figure 5-2: Classification of inbound aircraft according to the arrival direction

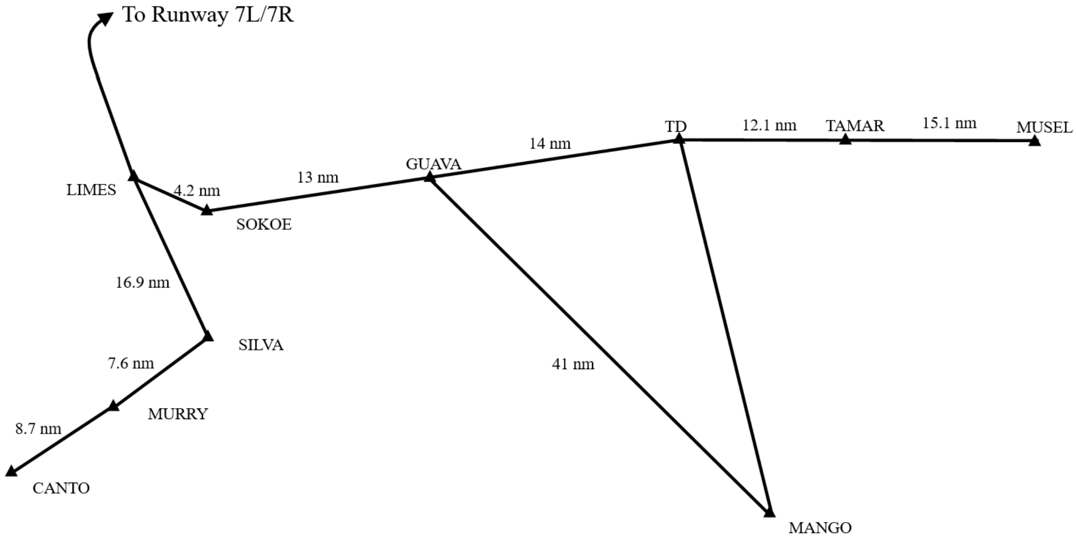


Figure 5-3: Schematic diagram of the arrival routes at VHHH airport

A special characteristic about southeast arrival is that from MANGO, there exists two possibilities for aircraft to join the MUSEL arrival stream: at GUAVA or TD. This gives the ATC controller more flexibility when handling arrival congestion. In this particular scenario setup, it is assumed that all aircraft in "Heavy" category will fly via TD while all others go via GUAVA.

According to figure A.7 and A.8, starting from way-point LIMES, all aircraft will fly north-west towards way-point STELA. Aircraft landing on runway 07R will turn to a heading of 40 degrees before intercepting the runway localizer. For landing on runway 07L, way-point TONIC is used instead (figure 5-4). The shared section of air-route between STELA and LIMES creates a bulk-neck for runway operations.

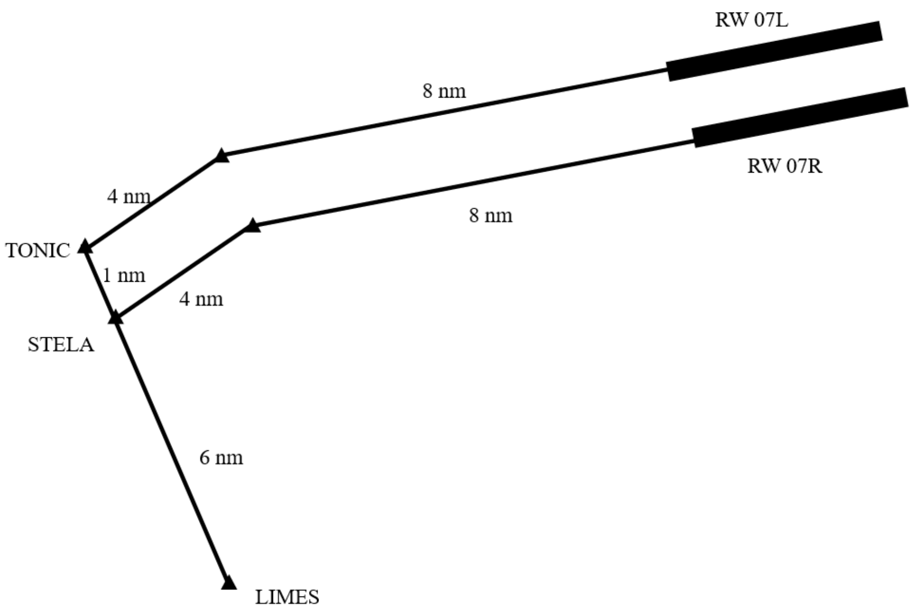


Figure 5-4: Schematic diagram of the landing routes at VHHH airport

5-4 Aircraft Generation

To simulate the arrival of aircraft from different directions, one additional property is added to the initialization of aircraft (section 4-2-2) to randomly generate a number ranging from 1 to 360, representing the heading. Then another random process will create a number representing the distance between the aircraft and way-point LIMES. When the newly generated aircraft has a distance less than 3 nautical miles different from another, it will be abandoned and a new set of values for heading and distance will be generated retrying the aircraft placement.

5-5 Verification of the Optimization Scheme Performance

For examining the performance of the proposed optimization scheme on the landing of aircraft at Hong Kong International Airport, a typical scenario of 20 aircraft is created. Figure 5-5 illustrates the initial positions of the aircraft with corresponding aircraft identification number next to it.

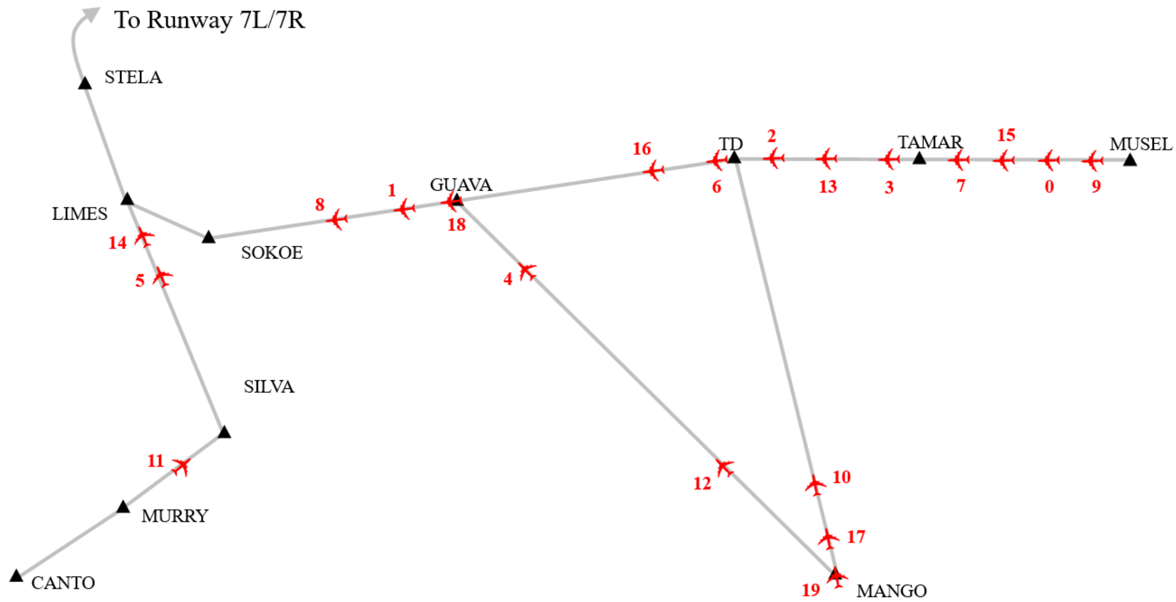


Figure 5-5: Initial positions of the aircraft

The benchmark for the optimization scheme is a fitness function measuring from 0 to 1. Higher fitness would be indicative of a better solution with lower amount of delay of the flights. As can be observed in figure 5-6 and 5-7, it took around 750 generations for the optimization to be saturated at a fitness value of around 0.25, which corresponds to a total delay of around 3 minutes.

Table 5-1 illustrates the optimization results of this scenario. It can be observed that the runways are alternately utilized for landing, which is logically rational. Also, it seems that most delays are happening with aircraft landing on runway 07L, which is at the far end of the approach route.

The reason behind this is two-folded. Firstly, the delay times are calculated based on the difference with the earliest possible landings. For this approach configuration , the earliest landing will always be on runway 07R which is closer to the way-point LIMES. Therefore, all aircraft landing on runway 07L will have an inherent disadvantage which can be translated to a delay time of approximately 0.2 minutes. Secondly, at the earlier phases of the simulation, runway 07L needs to handle a sequence of aircraft in large and

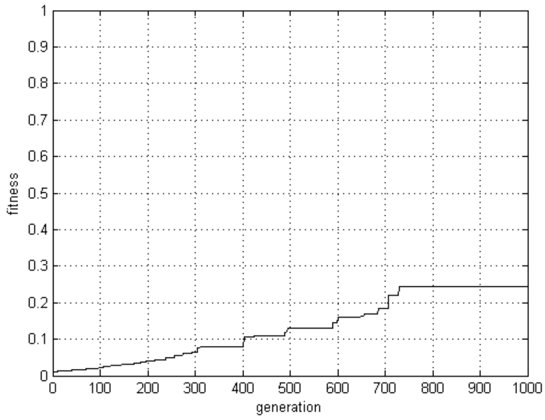


Figure 5-6: Changes in fitness values with increase in generations

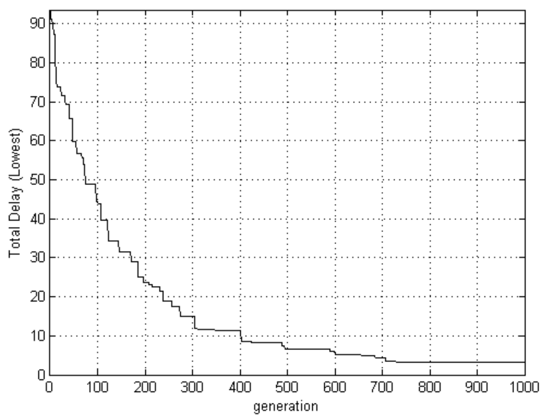


Figure 5-7: Changes of total delay with increase in generations

heavy category. Strict separation limit rules lead to delay propagation between aircraft 1, 11 and 16; contributing to a great proportion of the total delay.

Nonetheless, most aircraft is able to land at the earliest possible time and no plane experience a length delay. It is evident that the proposed genetic algorithm is able to generate a rather optimum landing sequence and runway choices out of some initially random number series.

5-6 Assumptions and Limitations

The optimization scheme is applied to a simplified scenario which imposes additional assumptions and limitations when comparing with real-world situations. One limitation of great importance is that, aircraft are only guaranteed to have no conflict at initialization and landing; therefore, they may violate the separation limit during the periods in between. This is especially a problem for airport like VHHH where approach routes to both runways are not operating fully independently with many junctions and shared sections.

Consequently, this further leads to the assumption that aircraft will somehow manage to consume the extra delay time in a way not causing conflicts with other inbound flights. Resolving this is a step of crucial importance in closing the gap between the ideal optimization results and real world operations. And this is one of the main motivations to design a real-time simulation as discussed in chapter 6.

Table 5-1: Optimization Results (NP=20)

Aircraft ID	Type	Landing Time (min, rounded)	Landing Runway	Delay Time (min, rounded)
14	Heavy	4	2 (07R)	0
5	Large	6	1 (07L)	0
8	Small	6.5	2 (07R)	0
1	Large	7.5	1 (07L)	0.5
18	Small	8.5	2 (07R)	0
11	Large	9	1 (07L)	1
4	Large	9.5	2 (07R)	0
16	Heavy	10.5	1 (07L)	0.5
6	Small	11.5	2 (07R)	0
2	Large	12	1 (07L)	0
13	Large	12.5	2 (07R)	0
3	Heavy	13.5	2 (07R)	0
12	Small	15	1 (07L)	0
7	Heavy	15	2 (07R)	0
15	Large	16	1 (07L)	0
0	Small	17	2 (07R)	0
9	Large	17.5	1 (07L)	0
10	Heavy	19	1 (07L)	0
17	Heavy	20	2 (07R)	0
19	Heavy	21	1 (07L)	0.5

Chapter 6

Simulation Design

6-1 Introduction

To visualize the optimization result and adapt for realistic situations, two forms of simulations are designed. In section 6-2, some shared basic elements of the simulation are discussed and presented. Then in section 6-3 and 6-4, detailed information is given for the direct simulation and the one with dynamic simulation and conflict resolution. This is followed by section 6-5 which is concerning result visualization.

6-2 Basic Elements of the Simulation Design

6-2-1 Movement of the Approaching Aircraft

For all aircraft before reaching LIMES, its position is defined by the distance to reach LIMES, the arrival direction and the aircraft type category. For every time step (t_{step}) in the simulation, the distance to reach LIMES will be reduced by

$$S_{toLIMES} = S_{toLIMES,previous} - V_{GS}t_{step} \tag{6-1}$$

For this simulation is concerned, it is assumed that the ground speed (V_{GS}) is equal to the indicated airspeed (thus neglecting density differences, wind influences, etc.). The indicated airspeed is determined by relevant speed limitations (commonly 250 $knots$ for aircraft flying below 10000 ft), optimization yielded target airspeed as well as temporary speed adjustment required by the conflict resolution algorithm. Also, for simplicity, the flight dynamics of aircraft has been neglected. As the result, all actions in changing the movement of aircraft can take effect instantly.

6-2-2 Movement of the Landing Aircraft

Once the aircraft reaches LIMES, a similar method is applied to define the location of the aircraft by its landing runway and the distance to the runway thread-hold. The airspeed of all aircraft will be set to 210 knots at LIMES. 12 nautical miles before touchdown, it will further reduce to 180 knots. The final approach speed will be set at a distance of 6 nautical miles from the runway thread-hold, and it has values of 160, 140 and 120 knots for aircraft in Heavy, Large and Small categories respectively.

6-2-3 New Script for Aircraft Generation

With the introduction of conflict resolution (section 6-4-3), the aircraft generation algorithm has been adapted for both simulation types to be more realistic. Now the newly generate aircraft will only get abandoned when it is in conflict (separation smaller than 3 nautical miles) with another one coming from the same direction category, or it is within 10 nautical miles of a point of juncture and in conflict with another one coming from the other direction category. This means aircraft further away from the juncture is allowed to have a direct conflict with another plane inbound from the other direction; and it is the job of conflict resolution scheme to timely and efficiently resolve the potential issues. This also allows for more aircraft to be generated in the optimization control airspace defined in section 4-2.

6-3 Direct Simulation of the Optimization Result

The genetic algorithm optimization results only assign each aircraft with a landing time and runway; however, how aircraft can achieve this in real-world actions is undetermined. In this direct simulation of the optimization result, manipulation of the target airspeed and introduction of holding bays are considered.

6-3-1 Determination of the Target Airspeed

In daily operations, altering the airspeed is a common tool air traffic controllers use to achieve the desired arriving time of the aircraft. Hence, it is considered as the primary means of aircraft adjustment in the simulation. For a given individual aircraft, its target airspeed is calculated as equation 6-2.

$$V_{target} = \frac{S_{toLIMES}}{\frac{S_{toLIMES}}{V_{normal}} + (t_{opt,result} - t_{scheduled})} \tag{6-2}$$

With $S_{toLIMES}$ the distance for the aircraft to be travelled to reach the way-point LIMES, V_{normal} the normal airspeed value, $t_{opt,result}$ the landing time given by the optimization result and $t_{scheduled}$ the scheduled arrival time. In this scenario, the minimum time required for the aircraft to reach the assigned runway is considered as the scheduled arrival time.

6-3-2 Holdings

Because of the aerodynamics characteristic of an aircraft, there will be a lowest airspeed limit. For intermediate descend phases, the highest flap settings are normally 15 *degrees* which corresponds to an airspeed of approximately 180 *knots* for most transportation aircraft types with typical payload weights. Therefore, 180 knots is considered as the minimum airspeed for all aircraft before reaching way-point LIMES. In case of 180 *knots* not enough to consume the delay time required, holding will be implemented at LIMES.

6-3-3 Limitation of the Scheme

Constrains in the optimization takes care of the separation of aircraft due to wake turbulence at landing. However, it does not monitor or generate solution for traffic conflicts at approach phases earlier. Another issue is the flexibility of the algorithm: situations are commonly varying and it is unrealistic to run the optimization once and use that as the guideline for every action. This is especially true when considering the fact that the optimization process makes use of many random parameters, thus its performance and reliability cannot be guaranteed. As the result, a new scheme of simulation with dynamic optimization is considered.

6-4 Simulation with Dynamic Optimization

6-4-1 Overview

The fundamental logic behind dynamic simulation is to incorporate a quick optimization scheme into the simulation loop. This quick optimization will inherent most of the parameter settings from the initial optimization; however the number of generations is significantly reduced to improve computational performance.

In this way, the whole system will become more flexible in dealing with real-time changes. These situations include handling of deviations of the aircraft airspeed from the assigned desire values; adding and removing of aircraft to the optimization scheme; applying real-time conflict resolution algorithm to meet the safety regulation; and to mitigate the overall risk when having occasional individual optimization failures. A flow chart (figure 6-1) can be used to visualize this scheme.

The process starts with parameter initialization where the initial chromosomes, aircraft types, directions and positions are determined. This is followed by an initial optimization

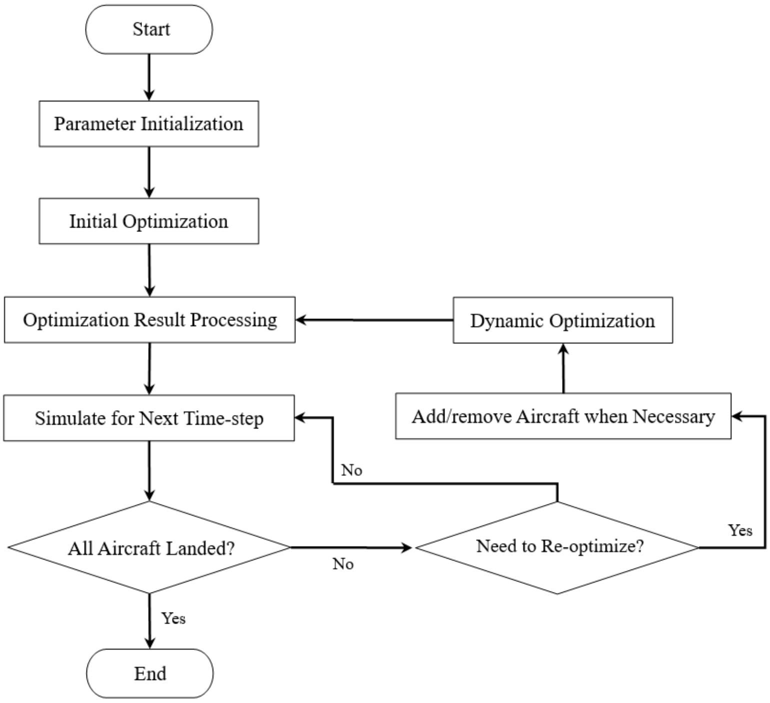


Figure 6-1: Flow chart of the dynamic optimization scheme

with larger maximum generation number. This is followed by a result processing scheme outputting the arrival information, target airspeed and the holding times.

With this the simulation can precede to the next time step with the new locations and airspeed of all aircraft determined. In this process, relevant constrains such as conflict resolutions are also incorporated. Next is to check whether the termination criteria (all aircraft landed) has been reached. In case not, then another check will be preformed to determine whether the situation need to be re-optimized with dynamic simulation. This decision could be made on time basis (re-optimize after certain time period) or triggered by certain events (e.g. aircraft entering or leaving the optimization region). To avoid potential problems, it is defined in the program that dynamic simulation will only be available when the number of aircraft in the optimization region is larger than 5. The simulation will terminate once all aircraft has landed.

6-4-2 Optimization with Pre-treatment

The prerequisite to have a dynamic optimization in the simulation loop is to have a faster optimization scheme. For this purpose, pre-treatment of the aircraft chromosomes is introduced to assist the optimization in the initial search phase. Logically speaking, the distance of the aircraft along the designate airway from the runway is a very good indication of how long does it need to land at the airport. In this particular case, the distance to LIMES can be used as a substitute since all inbound aircraft have to pass that way-point.

Therefore, half the population size of the initial aircraft chromosome will be replaced by an aircraft sequence determined based on their distance to LIMES. This serves as an initial baseline for the performance, and the other half random generated aircraft chromosome together with the reproduce, mate and mutate operations will ensure the biodiversity of the system to continue searching for more optimum solutions. The outcomes of the pre-treatment are analysed in section 7-2.

6-4-3 Conflict Resolution

With the simulation in real-time and dynamic optimization capable of flexibly handling situation changes, an extra layer of conflict resolution can be added to deal with flight conflicts in descend phases. Thus, for every time step moving forward in the simulation, every aircraft are checked for potential conflicts with previous planes. Therefore, aircraft with position farther away from the airport will make way for aircraft closer to landing in conflict resolution. When such actions are needed, two main resolution methods utilized: speed adjustments and holding.

Speed Adjustments

Speed adjustments are used to avoid potential conflicts to develop further into real concerns. Firstly, every aircraft has a buffer region 2 nautical miles larger than the 3 nautical miles radius separation limit. Once the subsequent aircraft has penetrate this buffer region, it will reduce airspeed to a value equivalent to the preceding aircraft, thus keeping a safe distance.

At airway intersections, a 10 nautical miles buffer region is established. Once a potential conflict for the subsequent aircraft is sensed by the system, it will reduce it to the minimum airspeed trying to clear the conflict.

Holding

If speed adjustments are unable to clear the conflict and the subsequent aircraft continue to get closer to the separation limit of the preceding aircraft, it will be put into a holding pattern immediately. For simplicity in this simulation, it is assumed (unrealistically) that this can occur at any location and for any time duration. In reality, there are specific holding bay locations that holdings must be executed, and there will also be a time lapse for aircraft to enter and exit holding patterns.

6-5 Result Visualization

The result visualization for the simulation is conducted while the simulation is running. The situation after each time-step will be plotted and captured as once frame, forming a smooth playing video. On the background is the air route map of VHHH airport (as shown in figure 5-4), and each aircraft is plotted on the map with a red cross representing its location and a label adjacent to it showing the flight information. Figure 6-2 is a single frame shot of the animation, with the callsign and aircraft type IDs corresponding to the tables in appendix B.

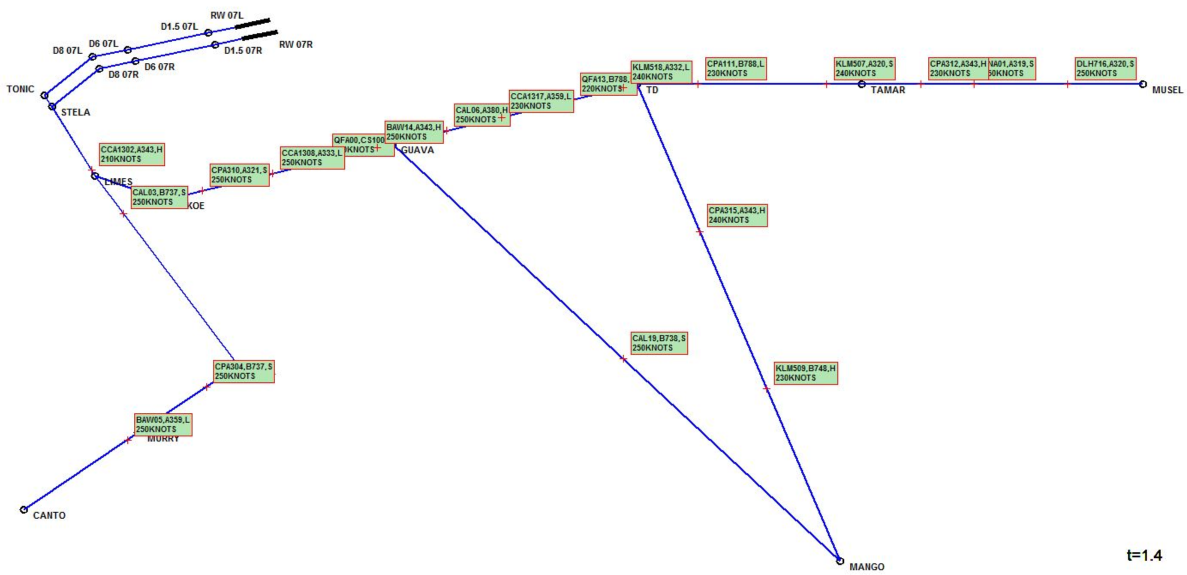


Figure 6-2: Visualization of the simulation

Part III

Results

Chapter 7

Result Comparison and Analysis

7-1 Introduction

In this chapter, the simulations designed in Chapter 6 are executed and compared. In section 7-2, the effects of optimization pre-treatment are analyzed and the choices of the number of generation parameters for the simulation are determined based on the analysis. Then in section 7-3, the comparison between direct simulation and simulation with dynamic optimization and conflict resolution is highlighted. This is followed by a brief conclusion in section 7-4.

7-2 Effects of Pre-treatment

A series of optimization calculations were conducted to examine the performance of pre-treatment in the algorithm. For a given scenario (identical for all runs with the same number of planes), optimization scheme with and without pre-treatment ran independently for 20 times. For pre-treatment, half of the initial aircraft chromosomes were substituted by a sequence of plane indexes based on their distance from the way-point LIMES. The average value for all 20 results are listed in Table 7-1 and especially for the value of the fitness function, a figure (Figure 7-1) is demonstrated.

It can be observed that in all situations, optimization with pre-treatment seems to have higher fitness values. It's interesting to note that although the absolute value of differences for the fitness between simulations with and without pre-treatment is more profound when the number of planes are low, the resultant difference in total delay of the flights are insignificant (lower than half a minute when the number of generations is larger than 200, i.e. when saturated). By contrast, when the number of aircraft is large, minor differences

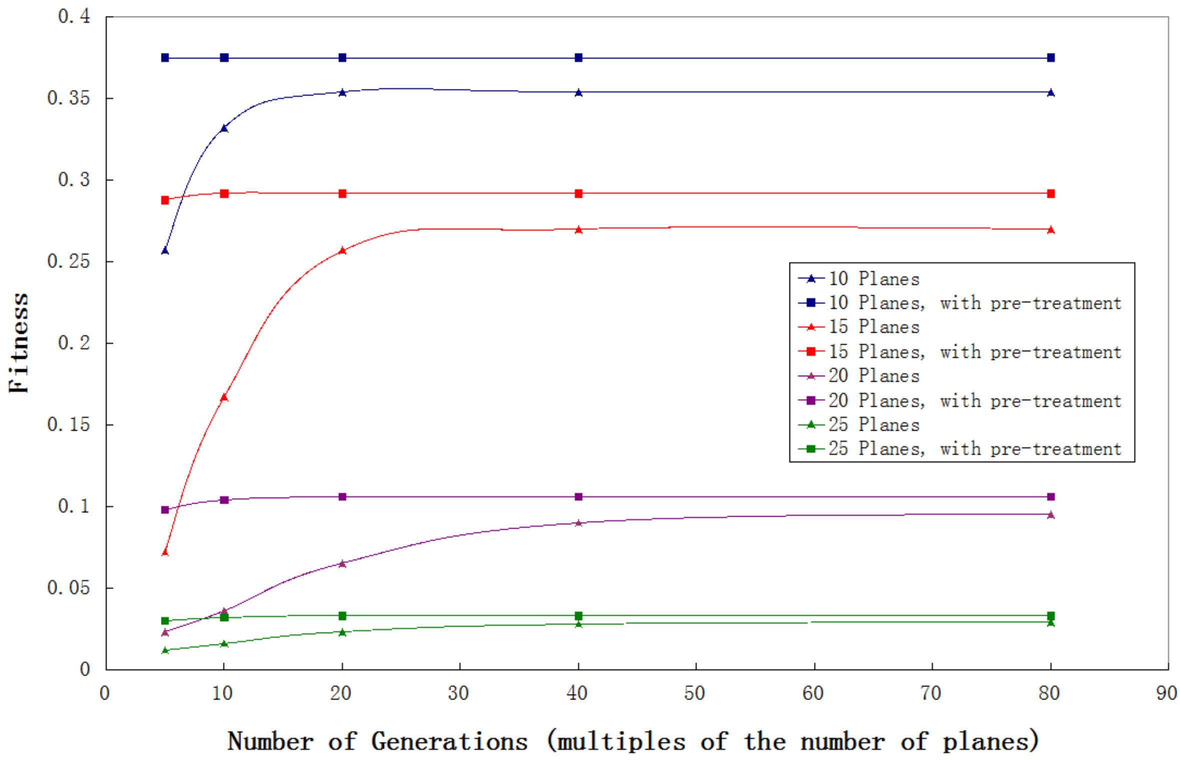


Figure 7-1: Effects of pre-treatment demonstrated by the value of fitness

in fitness could be indicative of a substantial increase in the total delay time as can be found in Table 7.1. Therefore, the benefit of pre-treatment can become more crucial when optimizing for a larger number of planes.

More importantly, the scheme can find a value very close to the optimum one with generation numbers as low as 10 times of the number of planes. This is significantly quicker than the generation number of 30 times of the number of planes for optimization without pre-treatment to reach a similar saturation condition. And for larger amounts of aircraft, this value may become as much as 70 times of the number of planes.

Based on these observations, it is determined that pre-treatment will be applied for all schemes in the simulations. For the initial optimization, a generation number of 20 times of the number of planes is selected because even in extreme conditions of 25 planes, the optimization is able to find a value very close to the saturated optimum. Whereas for dynamic simulation in the loop, a generation number of 10 times of the number of planes would be sufficient for a good balance between computation time and result accuracy.

Table 7-1: Effects of pre-treatment

Number of Planes	Generations	Pre-treatment	Fitness	Total Delay (min)
10	50	No	0.257	3.44
		Yes	0.375	1.67
	100	No	0.332	2.23
		Yes	0.375	1.67
	200	No	0.354	1.92
		Yes	0.375	1.67
	400	No	0.354	1.92
		Yes	0.375	1.67
	800	No	0.354	1.92
		Yes	0.375	1.67
15	75	No	0.072	14.08
		Yes	0.288	2.48
	150	No	0.167	5.75
		Yes	0.292	2.43
	300	No	0.257	2.96
		Yes	0.292	2.42
	600	No	0.270	2.76
		Yes	0.292	2.42
	1200	No	0.270	2.76
		Yes	0.292	2.42
20	100	No	0.023	43.22
		Yes	0.098	9.23
	200	No	0.036	27.35
		Yes	0.104	8.60
	400	No	0.065	15.06
		Yes	0.106	8.46
	800	No	0.090	10.446
		Yes	0.106	8.45
	1600	No	0.095	9.94
		Yes	0.106	8.45
25	125	No	0.012	85.43
		Yes	0.030	32.27
	250	No	0.016	62.43
		Yes	0.032	30.76
	500	No	0.023	43.58
		Yes	0.033	29.63
	1000	No	0.028	34.75
		Yes	0.033	29.42
	2000	No	0.029	33.67
		Yes	0.033	29.21

7-3 Effects of Dynamic Simulation and Conflict Resolution

Implementation of dynamic simulation and conflict resolution adds flexibility and realism to the simulation. However, the impact on the on time performance of the flights is difficult to determine. Dynamic simulation helps the system to jump out of an inferior condition determined by the previous calculations, potentially diminishing the total delay of the flights. Nevertheless, conflict resolution potentially delaying the flights by slowing down the airspeed and sometimes even putting them into holding patterns.

To examine the combined effects of these two items, a series of simulations were conducted with different number of planes and simulation type settings. For every setting, 5 independent runs with different scenarios are recorded. The benchmark of the scheme is the landing time of the last aircraft.

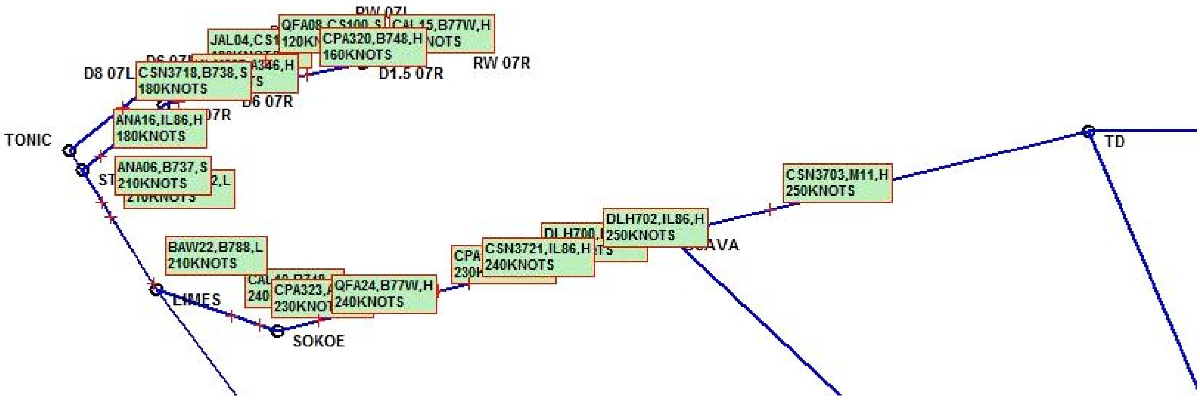
In table 7-2 illustrating the simulation results, bold font is used to highlight the simulation type that yields the earlier arrival. It can be observed that for very low number of planes, with lower chance for the conflict resolution to kick in, the result for direct and dynamic simulation most of the time coincides.

Yet, there still exists situations where the dynamic simulation shows a very profound edge. In the first run, the landing time is remarkably 8 minutes faster than the outcome of direct optimization. To examine the reasons behind this, the arrival matrix of the initial optimization is illustrated in table 7-3.

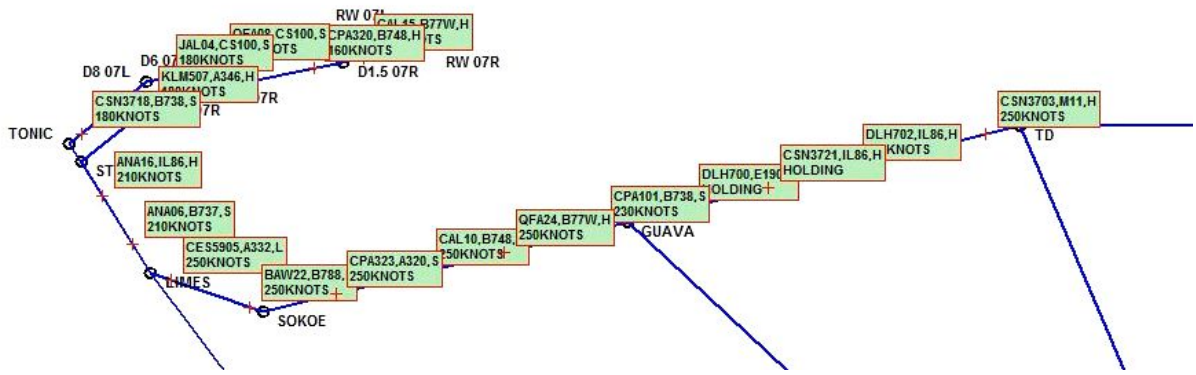
This is clearly a failed optimization. For some reason (not reproducible), the scheme got trapped in a local maximum and unable to exit it. This has led to late landings of some earlier arrived aircraft (e.g. plane 6 and 0) and earlier scheduled landing for some later arrived aircraft (e.g. plane 5), causing many lengthy holdings at way-point LIMES. This is the situation where the benefit of dynamic simulation can be clearly demonstrated that it has the capability to quickly turnover a failed previous optimization, minimizing the overall impact.

With the number of aircraft in the simulation increases and more conflict rises, conflict resolution start to further delay the flight. 15 planes seem to be the sweet spot which the on time performance of the schemes fully depends on the random generated scenario.

It's very pleasant to observe that with more than 20 planes, although conflict resolution becomes very complicated, the difference in the landing time of last aircraft is still rather low (less than 2 min). However, when considering the absolute chaos in figure 7-2a, contrasting to the orderly sequence in figure 7-2b, this small delay can be considered acceptable and worthy.



(a) direct simulation



(b) dynamic simulation with conflict resolution

Figure 7-2: Comparison between direct simulation and dynamic simulation with conflict resolution (NP=25, run No.4, t=12.85 min)

7-4 Conclusions

Analysis shown above have demonstrated that pre-treatment in the optimization scheme can greatly improve the result as well as significantly reduce the calculation time. This led to better real time performance, thus enables the design of simulations with dynamic simulation in the loop and some basic capability of conflict resolution.

In comparison to the direct simulation of the initial optimization results, dynamic simulation has shown its strength in flexibility and better handling of the occasional optimization failures. In most situations, conflict resolution algorithm is able to clear a potential penetration to the minimum safety separation limit with minor detrimental consequences on the arrival time.

Table 7-2: Effects of dynamic simulation and conflict resolution

Number of Planes	Run No.	Simulation Type	Time of Last Landing (min)
10	1	Direct	28.4
		Dynamics + Conflict Resolution	**20.5**
	2	Direct	21.7
		Dynamics + Conflict Resolution	21.7
	3	Direct	23.3
		Dynamics + Conflict Resolution	**22.3**
	4	Direct	20.9
		Dynamics + Conflict Resolution	20.9
	5	Direct	21.4
		Dynamics + Conflict Resolution	21.4
15	1	Direct	22.4
		Dynamics + Conflict Resolution	**21.0**
	2	**Direct**	**21.0**
		Dynamics + Conflict Resolution	21.2
	3	**Direct**	**21.0**
		Dynamics + Conflict Resolution	21.7
	4	Direct	22.6
		Dynamics + Conflict Resolution	**21.7**
	5	Direct	22.4
		Dynamics + Conflict Resolution	**21.1**
20	1	**Direct**	**21.5**
		Dynamics + Conflict Resolution	21.8
	2	**Direct**	**22.8**
		Dynamics + Conflict Resolution	24.0
	3	**Direct**	**21.8**
		Dynamics + Conflict Resolution	24.2
	4	Direct	23.1
		Dynamics + Conflict Resolution	22.0
	5	Direct	24.3
		Dynamics + Conflict Resolution	23.3
25	1	**Direct**	**22.8**
		Dynamics + Conflict Resolution	25.4
	2	**Direct**	**24.7**
		Dynamics + Conflict Resolution	25.8
	3	**Direct**	**23.9**
		Dynamics + Conflict Resolution	25.2
	4	**Direct**	**24.0**
		Dynamics + Conflict Resolution	25.7
	5	**Direct**	**24.2**
		Dynamics + Conflict Resolution	26.1

Table 7-3: Arrival matrix of the initial optimization in run 1 (NP=10)

Aircraft ID	Aircraft Type	Distance to LIMES	Landing Runway	Delay Time (min, rounded)
8	Large	3	2	0
3	Small	23	1	0
7	Heavy	31	1	0.5
5	Large	55	2	0
6	Large	15	2	11
2	Large	28	2	9.5
1	Heavy	33	2	9.5
9	Large	37	2	9.5
4	Large	45	2	9.5
0	Heavy	10	2	19

Chapter 8

Conclusions and Recommendations

In this chapter, the conclusions and recommendations that result from this thesis will be presented. The conclusions focus on explaining how this thesis has came up with a optimization algorithm, and how the findings from this thesis could be applied in a real world congested terminal airspace. The recommendations section will discuss the limitation of the current work and propose topics for follow-up studies.

8-1 Conclusions

According to the analysis on the current air traffic control system, most air traffic congestions have been occurred in the terminal airspace, and modification of arrival slot allocation is the current way to avoid congestion in this section. This methodology is based on the conventional first come first served, FCFS algorithm. It rearranges the arrival sequences according to the estimated time of arrival of the aircraft. However, this procedure has been found that it is empirical: experience based and usually not optimized. In fact, the nature of this research question is an optimization problem; unfortunately, it is found that there is no existing mathematical model which can directly be implemented into the congested TMA environment. Therefore it is essential to select a good feasible solution that is reasonably close to being optimal, while it should also be sufficiently efficient to deal with such large problem. Thus the use of heuristic method is considered preferable for this particular application.

One of the major difficulties for air traffic controller is the amount of choices of aircraft sequencing and landing runways that are available and must be determined for each incoming aircraft. The analysis demonstrates that genetic algorithm is very suitable for solving the typical multi-variables problem. Genetic algorithm offers a very intuitive and flexible modelling method with the arrival sequence and runway selection represented by chromosome sets. In addition, the performance is not very sensitive to parameter settings, and the objective function formulation is also rather simple and straightforward, which guarantees the overall computational requirements to be quite low. All these characteristics of the current setup serve as the foundation to adapted genetic algorithm for quick optimizations focusing on efficiency, thus suitable for real-time applications.

However, the optimization results themselves do not offer sufficient information regarding real-world implementations. Therefore, in the direct simulation, manipulation of the target airspeed and introduction of holding bays are considered as means to achieve the required arrival time. As the optimization is only executed once, it introduced many limitations. One example is that aircraft are only guaranteed by the optimization scheme to have no conflicts at initialization and landing; however, no guidance can be obtained on preventing separation limit violations for the periods in between. Resolving problems like this is a crucial important step for closing the gap between the ideal optimization results and real world operations. And this was one of the major motivations to design a dynamic simulation in this thesis.

Since it is unrealistic to optimize once and use that as the guideline for all subsequent actions, a new scheme of simulation with dynamic optimization is introduced. The fundamental logic behind it is to incorporate a quick optimization scheme into the simulation loop. This genetic algorithm based quick optimization inherent most of the parameter settings from the initial optimization; while the number of generations is significantly reduced to improve computational performance.

In addition to the dynamic simulation, an extra layer of conflict resolution is added to deal with flight conflicts in descend phases. For every time step moving forward in the simulation, all aircraft are checked for potential conflicts with previous planes. Therefore, aircraft with position further away from the airport will make way for aircraft closer to landing in conflict resolution. When such actions are needed, two main resolution methods will be utilized: speed adjustments and holding.

In comparison to the direct simulation of the initial optimization results, dynamic simulation has shown its strength in flexibility and better handling of the occasional optimization failures. In most situations, conflict resolution algorithm is able to clear a potential penetration to the minimum safety separation limit with minor detrimental consequences on the arrival time.

It is important to note that the main finding of this thesis is not to generate obviously improved results of an idealized situation; but rather to provide a useful platform that is capable of incorporating various factors that may occur in practical operations. This means that instead of searching for the guaranteed global optimum in simple ideal models; this thesis provide a heuristic method which can be easily adapt into a decision support tool aiding air traffic controller in choosing the best out of infinite number of options.

To demonstrate the performance of the proposed optimization scheme on two-runway equipped airports, the standard arrival routes of Hong Kong International Airport are selected for the validation of the optimization scheme and simulation design. It is evident that the proposed genetic algorithm based optimization design is able to generate a rather optimum landing sequence and runway allocation, thus providing the air traffic controllers the ability to further improve the terminal airspace throughput while maintaining aircraft safety separations. Ultimately, the implementation of such optimization approach will reduce the terminal airspace congestion without adversely effecting on the air traffic controllers' workload.

8-2 Recommendations

To implement this model into the real-world air traffic system, there are still several dynamic factors need to be considered. This derives to the limitation of this thesis where future researches could be focusing on.

- According to the simulation model designed in this thesis, conflict of aircraft is resolved by speed adjustment and holding. In this simulation model, those two manoeuvres are both done instantly. However, this is unrealistic in the actual world.
- In the actual terminal airspace environment, wind speed and direction is varies, which brings more uncertainties to the air traffic controller. Those uncertainties haven't been considered in the thesis.
- In addition, aircraft might fly unexpectedly during landing. One of the example is that pilot might fly off course in the STARs to avoid cumulonimbus clouds.

In addition, for developing a feasible automatic platform for solving future terminal airspace congestion problems, there are several possibilities to extend the research on.

- It is determined that one of the vulnerability of congested terminal airspace is due to the bottle neck of STARs. Therefore, it is possible to design a dynamic STAR besides the standard STAR procedures.
- Multiple airports with various runway configurations can be evaluated, which can stand out as another scenario to compare with Hong Kong International Airport.
- Flight dynamic variables haven't been concerned in this work. Before this model can be utilized in real-world air traffic environment, flight dynamic variables need to be incorporated in this model. Those variables including changing of aircraft weight due to fuel consumption, changing of wind speed, and even human factors need also to be taken into account.

Part IV

Appendices

Appendix A

Aerodrome Charts of VHHH

The airport charts presented in this appendix are used for the design of the arrival traffic routes in the simulation. They were obtained from the Civil Aviation Department Hong Kong [31].

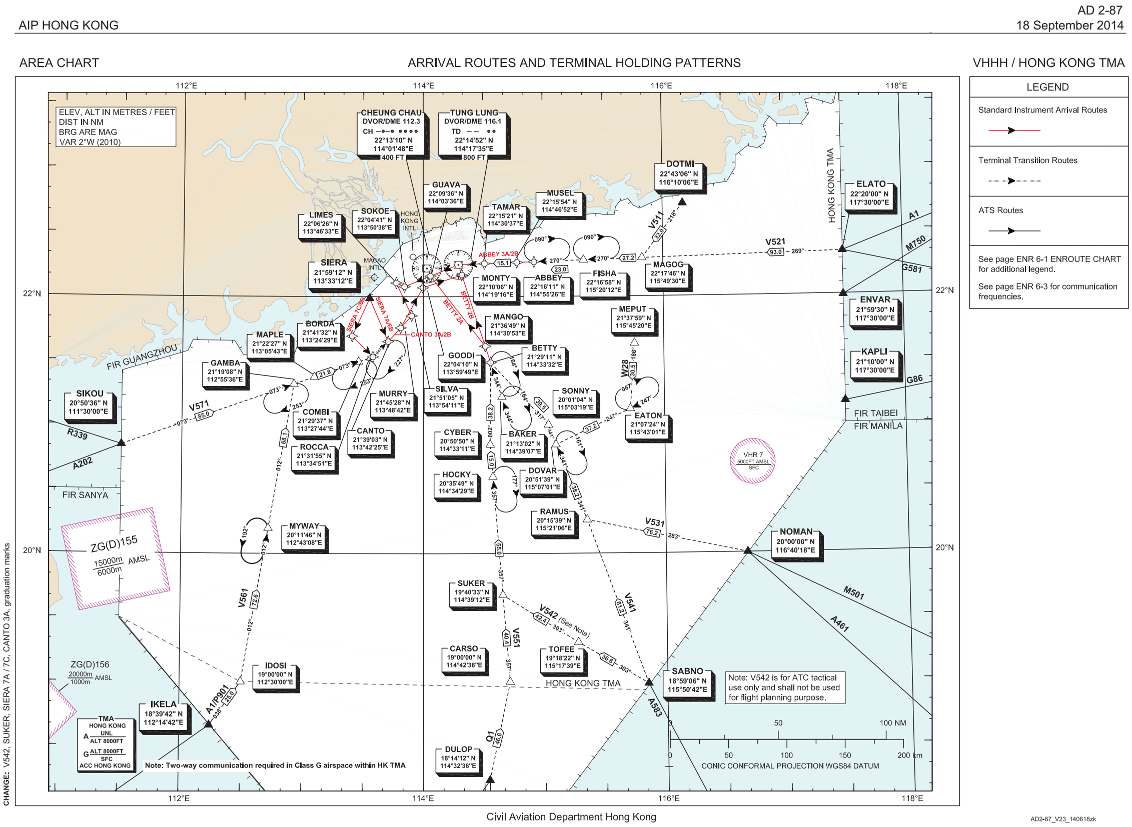


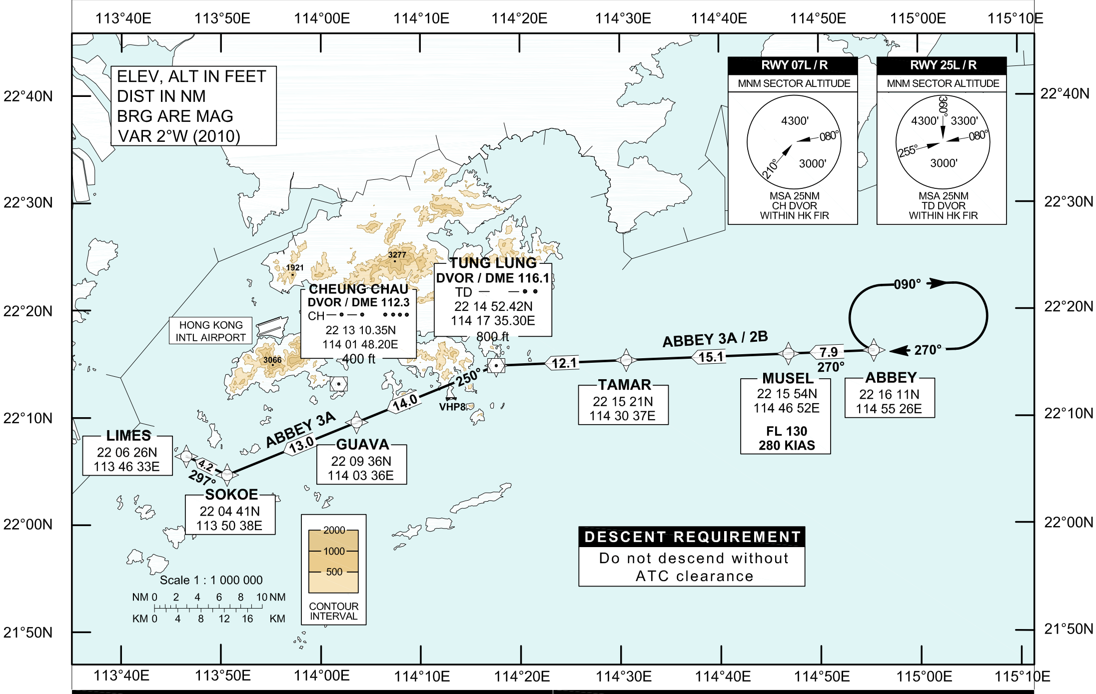
Figure A-1: Overview of arrival directions and routes

STANDARD ARRIVAL CHART-INSTRUMENT (STAR) - ICAO

Transition Altitude 9 000 ft
HONG KONG RADAR 126.5

HONG KONG / Intl (VHHH)
RNAV (GNSS) ABBEY 3A STAR RWY 07L / 07R
RNAV (GNSS) ABBEY 2B STAR RWY 25L / 25R

1. For RNAV (GNSS) STAR aircraft must be approved by State of Registry in accordance with ICAO Basic-RNP 1 standard or equivalent (see GEN 1.5 para 3.5.2 on page GEN 1.5-2). Carriage of certified GNSS receiver is mandatory.
2. Conventional Procedure is for exclusive use by airline operators which have been granted prior approval. For application, see VHHH AD 2.22 para 7.1.3 on page AD 2-32.



ABBEY 3A STAR RWY 07L / RWY 07R

Basic-RNP 1 Procedure
(Mandate procedure available to aircraft appropriately equipped and approved)
ABBEY - MUSEL[F130;K280] - TAMAR - TD[L] - GUAVA - SOKOE[R] - LIMES
Expect ILS approach. Descend as directed by ATC.

Conventional Procedure
(Use of procedure subject to prior approval, see Note 2.)
From ABBEY proceed direct to MUSEL then TAMAR.
From TAMAR proceed direct to TD DVOR then GUAVA (TD R250 / D14 NM). From GUAVA proceed direct to SOKOE (TD R250 / D27 NM) then LIMES. Expect ILS approach. Descend as directed by ATC.

IF TD DVOR is not available
From MUSEL proceed direct to TAMAR then reporting point TD. From reporting point TD proceed direct to GUAVA then SOKOE. From SOKOE proceed direct to LIMES. Descend as directed by ATC.

ABBEY 2B STAR RWY 25L / RWY 25R

Basic-RNP 1 Procedure
(Mandate procedure available to aircraft appropriately equipped and approved)
ABBEY - MUSEL[F130;K280] - TAMAR - TD
Expect ILS approach. Descend as directed by ATC.

Conventional Procedure
(Use of procedure subject to prior approval, see Note 2.)
From ABBEY proceed direct to MUSEL then TAMAR.
From TAMAR proceed direct to TD DVOR.
Expect ILS approach. Descend as directed by ATC.

IF TD DVOR is not available
From MUSEL proceed direct to TAMAR then reporting point TD. Descend as directed by ATC.

DESCENT REQUIREMENT
Cross MUSEL at F130. **DO NOT DESCEND WITHOUT ATC CLEARANCE.**

SPEED CONTROL
Aircraft shall fly at 280 KIAS by MUSEL.

HOLDING
The holding pattern for ABBEY STARs is established at ABBEY. If holding is required, each flight will be instructed individually.

ALTERNATIVE HOLDING
In order to provide traffic management flexibility during peak periods of arrival or adverse weather situation in Hong Kong TMA, traffic may be instructed to hold at BETTY or other terminal holding as directed by ATC.

LOSS OF COMMUNICATION
In the event of a loss of communication aircraft shall comply with the descent requirement and the STAR track above.
Thence:
For RWY 07L/R, maintain F130 to LIMES. Join LIMES holding pattern and descend to 4 500 ft in the hold, then carry out the appropriate ILS approach procedure.
For RWY 25L/R, maintain F130 to TD DVOR. Join TD DVOR holding pattern and descend to 4 500 ft in the hold, then carry out the appropriate ILS approach procedure.

Figure A-2: Arrival route via ABBEY

AD 2-98 BETTY
22 August 2013

AIP HONG KONG

STANDARD ARRIVAL CHART-INSTRUMENT (STAR) - ICAO

Transition Altitude 9 000 ft

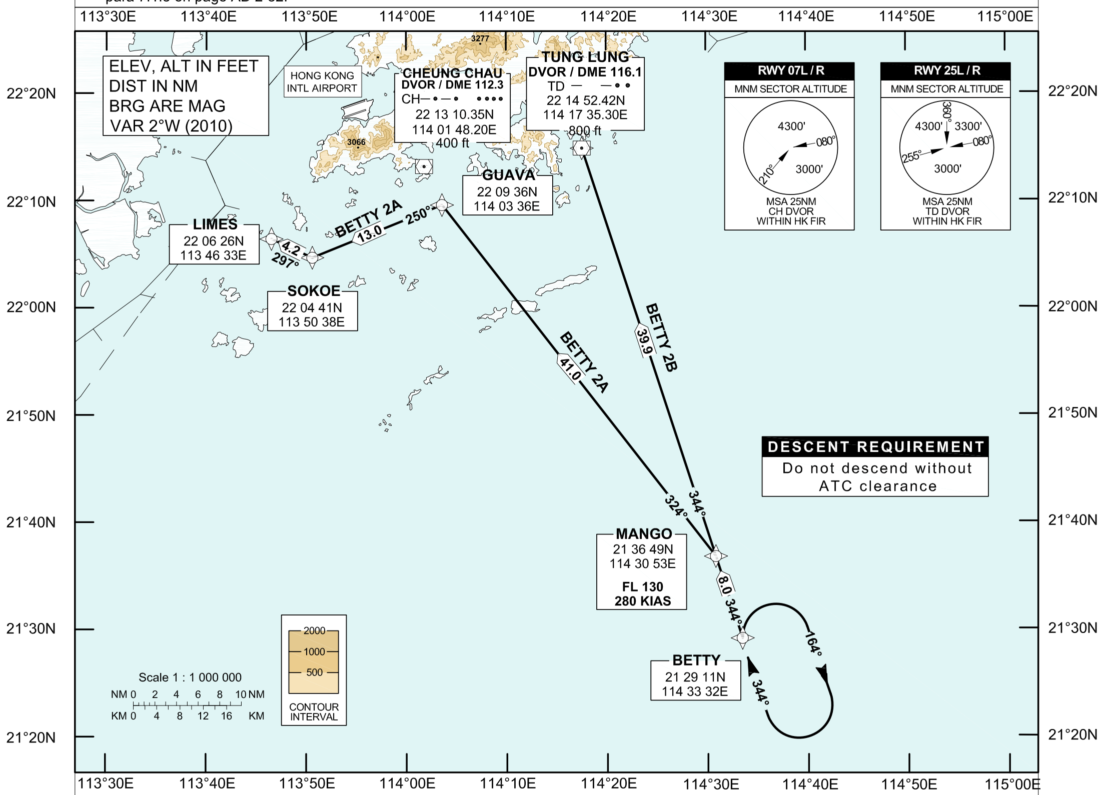
HONG KONG RADAR 126.3

HONG KONG / Intl (VHHH)

RNAV (GNSS) BETTY 2A STAR RWY 07L / 07R

RNAV (GNSS) BETTY 2B STAR RWY 25L / 25R

1. For RNAV (GNSS) STAR aircraft must be approved by State of Registry in accordance with ICAO Basic-RNP 1 standard or equivalent (see GEN 1.5 para 3.5.2 on page GEN 1.5-2). Carriage of certified GNSS receiver is mandatory.
2. Conventional Procedure is for exclusive use by airline operators which have been granted prior approval. For application, see VHHH AD 2.22 para 7.1.3 on page AD 2-32.



BETTY 2A STAR RWY 07L / RWY 07R

Basic-RNP 1 Procedure

(Mandate procedure available to aircraft appropriately equipped and approved)

BETTY - MANGO[F130;K280;L] - GUAVA[L] - SOKOE[R] - LIMES

Expect ILS approach. Descend as directed by ATC.

Conventional Procedure

(Use of procedure subject to prior approval, see Note 2.)

From BETTY proceed direct to MANGO then GUAVA (TD R250 / D14 NM). From GUAVA proceed direct to SOKOE (TD R250 / D27 NM) then LIMES. Expect ILS approach. Descend as directed by ATC.

If TD DVOR is not available

From MANGO proceed direct to GUAVA then SOKOE. From SOKOE proceed direct to LIMES. Descend as directed by ATC.

BETTY 2B STAR RWY 25L / RWY 25R

Basic-RNP 1 Procedure

(Mandate procedure available to aircraft appropriately equipped and approved)

BETTY - MANGO[F130;K280] - TD

Expect ILS approach. Descend as directed by ATC.

Conventional Procedure

(Use of procedure subject to prior approval, see Note 2.)

From BETTY proceed direct to MANGO then TD DVOR.
Expect ILS approach. Descend as directed by ATC.

If TD DVOR is not available

From MANGO proceed direct to reporting point TD.
Descend as directed by ATC.

DESCENT REQUIREMENT

Cross MANGO at F130. **DO NOT DESCEND WITHOUT ATC CLEARANCE.**

SPEED CONTROL

Aircraft shall fly at 280 KIAS by MANGO.

HOLDING

The holding pattern for BETTY STARs is established at BETTY. If holding is required, each flight will be instructed individually.

ALTERNATIVE HOLDING

In order to provide traffic management flexibility during peak periods of arrival or adverse weather situation in Hong Kong TMA, traffic may be instructed to hold at BAKER, CANTO or other terminal holding as directed by ATC.

LOSS OF COMMUNICATION

In the event of a loss of communication aircraft shall comply with the descent requirement and the STAR track above.
Thence:
For RWY 07L/R, maintain F130 to LIMES. Join LIMES holding pattern and descend to 4 500 ft in the hold, then carry out the appropriate ILS approach procedure.
For RWY 25L/R, maintain F130 to TD DVOR. Join TD DVOR holding pattern and descend to 4 500 ft in the hold, then carry out the appropriate ILS approach procedure.

Civil Aviation Department Hong Kong

AD2-98 BETTY_V06_130725zk

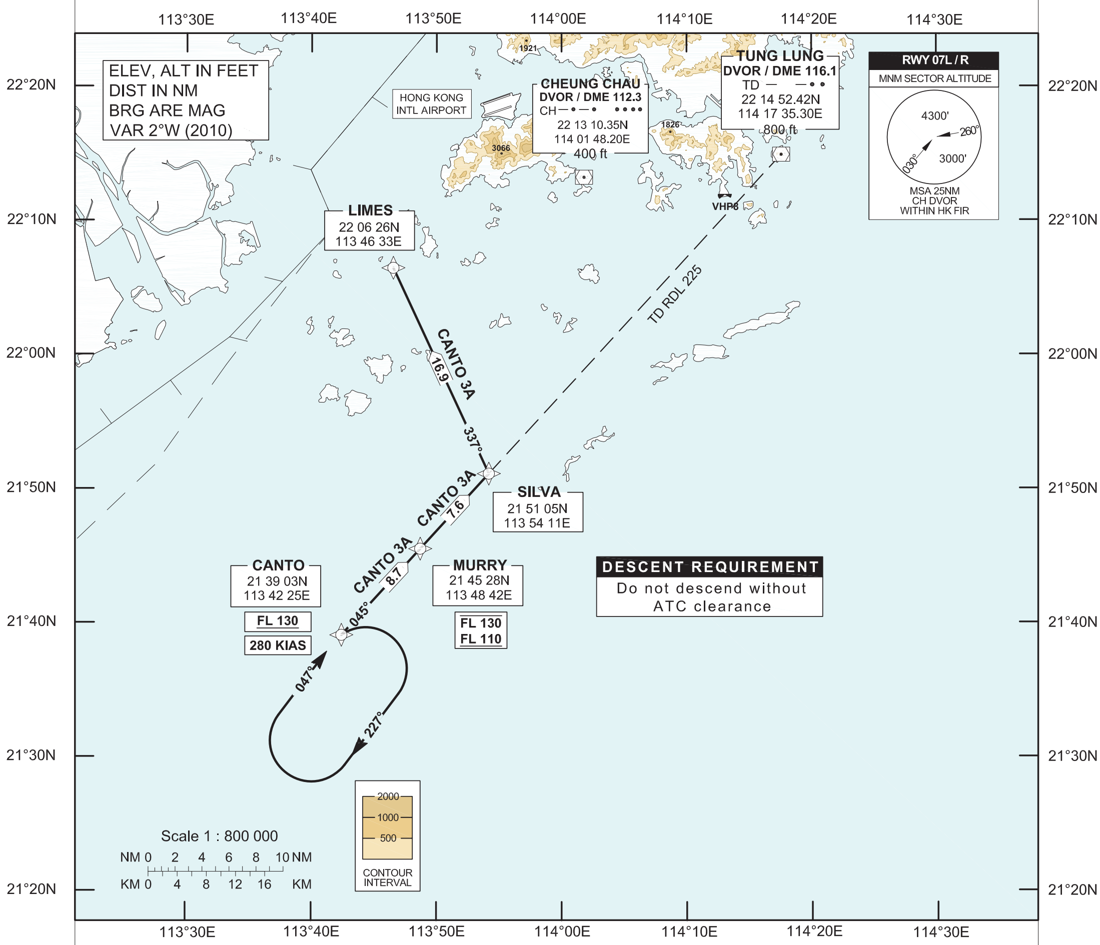
Figure A-3: Arrival route via MANGO

STANDARD ARRIVAL CHART-INSTRUMENT (STAR) - ICAO

Transition Altitude 9 000 ft
HONG KONG RADAR 127.55

HONG KONG / Intl (VHHH)
RNAV (GNSS) CANTO 3A STAR
RWY 07L / 07R

1. For RNAV (GNSS) STAR aircraft must be approved by State of Registry in accordance with ICAO Basic-RNP 1 standard or equivalent (see GEN 1.5 para 3.5.2 on page GEN 1.5-2). Carriage of certified GNSS receiver is mandatory.
2. Conventional Procedure is for exclusive use by airline operators which have been granted prior approval. For application, see VHHH AD 2.22 para 7.1.3 on page AD 2-32.



CANTO 3A STAR RWY 07L / RWY 07R

Basic-RNP 1 Procedure
(Mandate procedure available to aircraft appropriately equipped and approved)
CANTO [FL130+,K280] - MURRY [FL130-FL110] - SILVA [L] - LIMES
Expect ILS approach. Descend as directed by ATC.

Conventional Procedure
(Use of procedure subject to prior approval, see Note 2.)
From CANTO proceed direct to MURRY then SILVA. From SILVA turn left to LIMES. Expect ILS approach. Descend as directed by ATC.

DESCENT REQUIREMENT
Cross CANTO FL 130 or above. Cross MURRY between FL 130 and FL 110.
DO NOT DESCEND WITHOUT ATC CLEARANCE.

SPEED CONTROL
Aircraft shall fly at 280 KIAS by CANTO.

HOLDING
The holding pattern for CANTO STAR is established at CANTO. In the event of holding, each flight will be instructed individually.

ALTERNATIVE HOLDING
In order to provide traffic management flexibility during peak periods of arrivals or adverse weather situation in Hong Kong TMA, traffic may be instructed to hold at COMBI, BETTY or other terminal holdings (see ENR3.6) as directed by ATC.

LOSS OF COMMUNICATION
In the event of a loss of communication aircraft shall comply with the descent requirement and the STAR track above. Maintain FL 130 to LIMES. Join LIMES holding pattern and descend to 4 500 ft in the hold, then carry out the appropriate ILS approach procedure.

CHANGE: CANTO FL130+, MURRY FL130-FL110, CANTO 3A.

Civil Aviation Department Hong Kong

AD2-98_CANTO_A_V20_140429kc

Figure A-4: Arrival route via CANTO

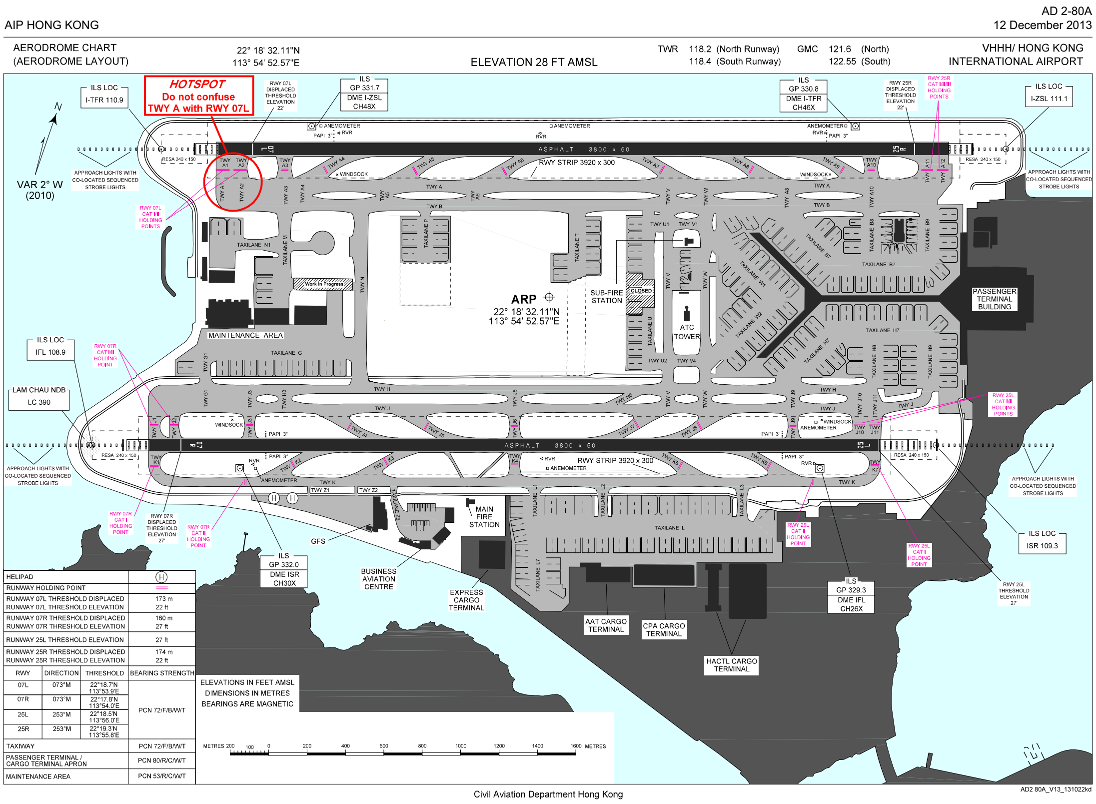
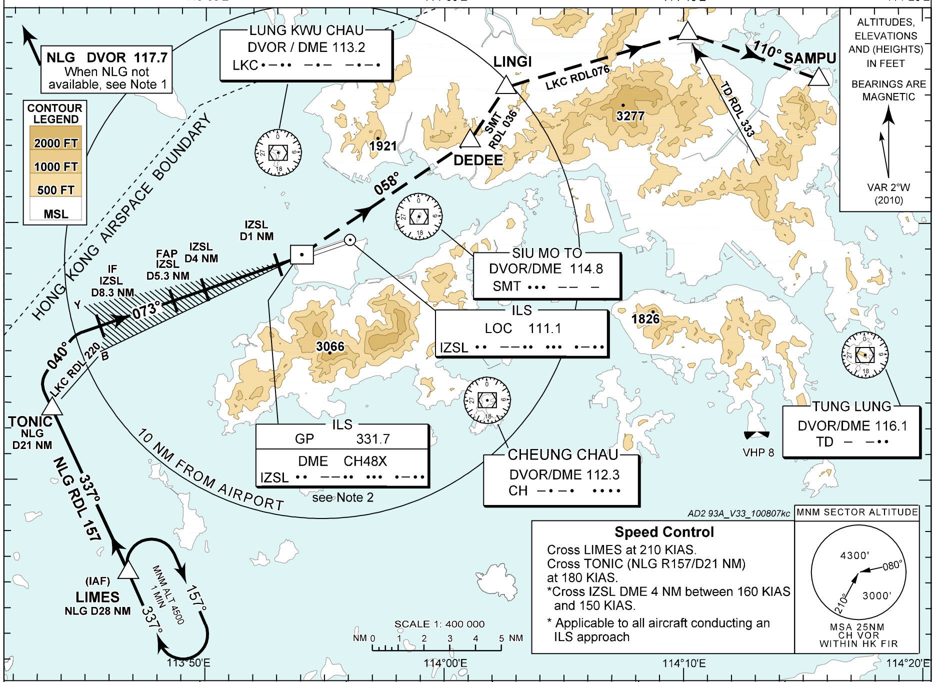


Figure A-5: Airport overview (VHHH)

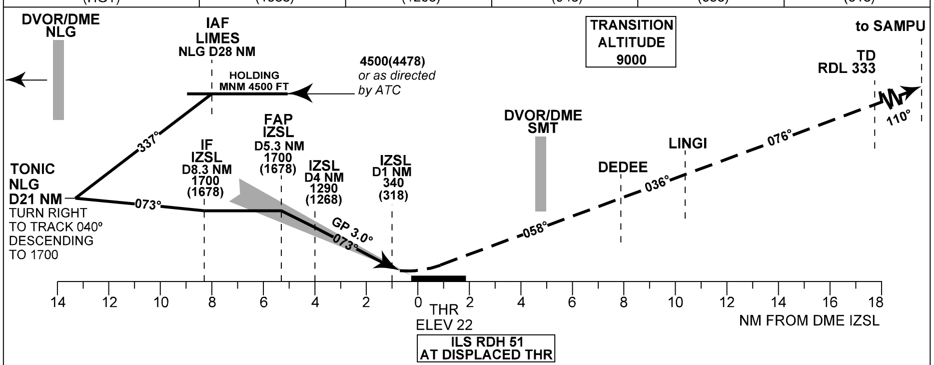
AD2-93A
AIP HONG KONG 26 August 2010

INSTRUMENT APPROACH CHART - ICAO	AERODROME ELEV 28 FT (HEIGHTS RELATED TO THR RWY 07L - ELEV 22 FT)	HONG KONG TOWER NORTH 118.2 HONG KONG APPROACH 119.1 HONG KONG DIRECTOR 119.5	**HONG KONG / Intl (VHHH)** **ILS RWY 07L** **CAT II**

WARNING **LOC IZSL UNUSABLE BEYOND 28° RIGHT OF COURSE**



DME IZSL	5	4	3	2	1
ALT 3° APCH (HGT)	1610 (1588)	1290 (1268)	970 (948)	660 (638)	340 (318)



NOTE 1 **IF NLG DVOR NOT AVBL**
At LIMES track 337ºM. After crossing LKC DVOR RDL 203 descend to 2,000 ft. Crossing LKC DVOR RDL 220 turn right to track 040ºM to intercept LOC descending to 1,700 ft.

NOTE 2 DME is required. If unable to receive IZSL DME pilot shall advise ATC and will receive equivalent radar ranges for FAP (IZSL DME 5.3 NM) and OM Fix (IZSL DME 4 NM).

GS KT	160	140	120	100	80
FT Per MINUTE	840	740	630	530	420

AIRCRAFT CATEGORIES	CAT I * OCA (OCH)	CAT II * OCA (OCH)	VISUAL CIRCLING
A, B, C, D	222 ft (200 ft)	122 ft (100 ft)	NOT AVAILABLE

*** These procedures require a missed approach climb gradient of 7% (426 ft/NM). For aircraft which can only achieve a 2.5% (152 ft/NM) climb gradient, the CAT I OCA (OCH) is 1,332 ft (1,310 ft).**

MISSED APPROACH

Ahead to 300ft, then turn left on track 058M and climb to 5000ft. Continue climb on track 058M, and intercept SMT 036R to LINGI then turn right on LKC 076R outbound. Crossing TD333R, track 110M to SAMPU and expect radar vector.

NOTE 3 NO Turn before IZSL D0.2NM (RWY07L THR).
NOTE 4 Climbing gradient of 7% is required.
NOTE 5 A speed restriction of 230 KIAS is required.
NOTE 6 When SMT DVOR is not available, ahead to 300', then turn left on track 058M and climb to 5000' (NO turn before IZSL D0.2 NM) then expect radar vectors.

Civil Aviation Department Hong Kong

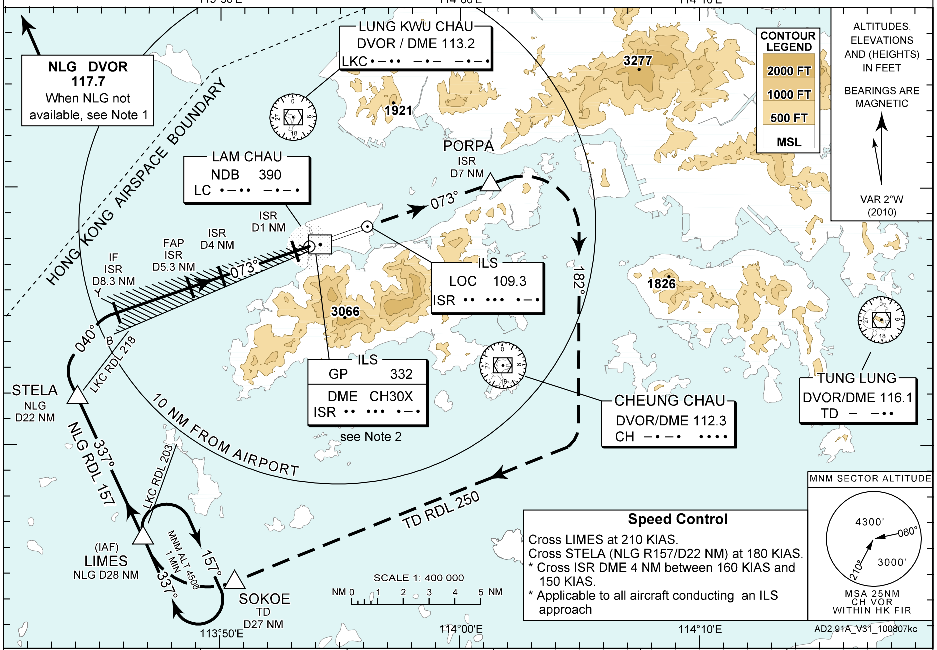
Figure A-6: Approach route for runway 7L

AD2-91A

AIP HONG KONG 26 August 2010

INSTRUMENT APPROACH CHART - ICAO	AERODROME ELEV 28 FT (HEIGHTS RELATED TO THR RWY 07R - ELEV 27 FT)	HONG KONG TOWER SOUTH 118.4 HONG KONG APPROACH 119.1 HONG KONG DIRECTOR 119.5	**HONG KONG / Intl (VHHH)** **ILS RWY 07R** **CAT II**

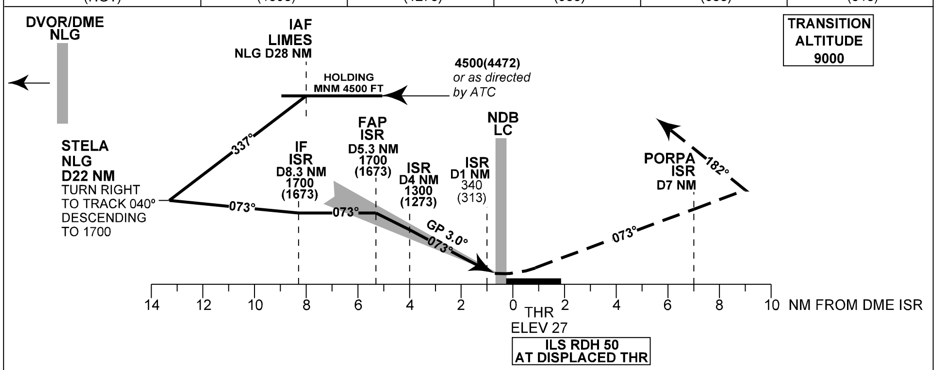
WARNINGS
1. **LOC ISR UNUSABLE BEYOND 25° LEFT OF COURSE AND 19° RIGHT OF COURSE**
2. **GP SIGNAL MAY BE LIABLE TO INTERFERENCE FROM GROUND TRAFFIC DURING CAT I OPERATIONS**



Speed Control

Cross LIMES at 210 KIAS.
Cross STELA (NLG R157/D22 NM) at 180 KIAS.
* Cross ISR DME 4 NM between 160 KIAS and 150 KIAS.
* Applicable to all aircraft conducting an ILS approach

DME ISR	5	4	3	2	1
ALT 3° APCH (HGT)	1620 (1593)	1300 (1273)	980 (953)	660 (633)	340 (313)



NOTE 1 **IF NLG DVOR NOT AVBL**
At LIMES track 337ºM. After crossing LKC DVOR RDL 203 descend to 2,000 ft. Crossing LKC DVOR RDL 218 turn right to track 040ºM to intercept LOC descending to 1,700 ft.

NOTE 2 DME is required. If unable to receive ISR DME pilot shall advise ATC and will receive equivalent radar ranges for FAP (ISR DME 5.3 NM) and OM Fix (ISR DME 4 NM).

GS KT	160	140	120	100	80
FT Per MINUTE	840	740	630	530	420

AIRCRAFT CATEGORIES	CAT I * OCA (OCH)	CAT II * OCA (OCH)	VISUAL CIRCLING
A, B, C, D	227 ft (200 ft)	127 ft (100 ft)	NOT AVAILABLE

*** These procedures require a missed approach climb gradient of 4% (243 ft/NM) until passing 1,300 ft. For aircraft which can only achieve a 2.5% (152 ft/NM) climb gradient. the CAT I OCA (OCH) is 348 ft (320 ft).**

MISSED APPROACH

Climb to 5,000 ft. Remain on the extended runway centreline tracking 073ºM (or bearing 073ºM to/from LC NDB) until PORPA (ISR DME 7 NM). At PORPA turn right to track 182ºM to establish on TD DVOR RDL 250 outbound to SOKOE then turn right to LIMES. Join LIMES holding pattern or as directed by ATC.

NOTE 3 A speed restriction of 210 KIAS is required until established on track 182ºM.

NOTE 4 Initial missed approach turn must not be made before fix PORPA (ISR DME 7 NM)

IF TD DVOR IS NOT AVAILABLE

Climb to 5,000 ft. Remain on the extended runway centerline tracking 073ºM (or bearing 073ºM to/from LC NDB) until PORPA (ISR DME 7 NM). At PORPA turn right to track 182ºM. Expect radar vectors to LIMES.

Civil Aviation Department Hong Kong

Figure A-7: Approach route for runway 7R

Appendix B

Simulation Visualization

Table B-1: Airline names and corresponding call sign

Airline	**Call Sign**
Cathay Pacific	CPA
China Eastern	CES
Air China	CCA
China Southern	CSN
KLM	KLM
Lufthansa	DLH
British Airways	BAW
Qantas	QFA
Emirates	UAE
Japan Airlines	JAL
All Nippon Airlines	ANA
China Airlines	CAL

Table B-2: Aircraft model abbreviations for different size categories

Size Category	Aircraft Model	Abbreviation
Heavy(H)	Airbus A380-800	A380
	Boeing 777-300ER	B77W
	Boeing 777-200	B772
	Airbus A340-600	A346
	Boeing 747-400ER	B744
	Boeing 747-8i	B748
	McDonnell Douglas MD-11	M11
	Airbus A340-300	A343
	Ilyushin Il-86	IL86
Large(L)	Airbus A330-200	A332
	Airbus A330-300	A333
	Airbus A350-800XWB	A358
	Airbus A350-900XWB	A359
	Boeing 767-300ER	B763
	Boeing 757-200	B752
	Boeing 787-8	B788
	Boeing 787-9	B789
	Boeing 767-200	B762
Small(S)	Airbus A319	A319
	Airbus A320	A320
	Airbus A321	A321
	Boeing 737-700	B737
	Boeing 737-800	B738
	Boeing 737-900	B739
	COMAC C919	C919
	Bombardier CS100	CS100
	COMAC ARJ21	ARJ21
	Embraer 190	E190

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