Estimation of runway capacity at Changi Airport using AirTOp and Monte Carlo analysis

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

Masters Dissertation

**“Estimation of runway capacity at Changi Airport using
AirTOP and Monte Carlo analysis”.**

Supervisor : Assoc. Prof Zhong Zhaowei

Submitted By

Dhir Varun

(Metric Number: G1401639G)

School of Mechanical and Aerospace Engineering

A Master's Thesis

Presented to

NANYANG TECHNOLOGICAL UNIVERSITY

In Partial Fulfillment Of The

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Abstract

The issue of future capacity of Changi airport in Singapore is currently the subject of much debate. Runway occupancy time is an important control parameter in enhancing the use of current infrastructure to increase capacity of existing runways. Due to land availability constraints in Singapore the construction of new runways is also limited. The realistic estimates of the effects of capacity enhancement are desirable, but these estimates are difficult. This research estimates the runway occupancy time and maximum runway capacity at Changi airport using AirTOp simulation software and Monte Carlo analysis.

A model of Changi airport was simulated using AirTOp simulator software. The evaluation of runway occupancy time and runway capacity was done based on the flight arrival/departure data captured for 6600 movements from the Changi airport group website. The study analyzes runway occupancy times and runway capacity under different traffic mix scenarios. It also takes into account the increase in capacity that can be achieved after construction of the third runway is over.

The results of this study indicate that runway occupancy time is not only dependant on size of the aircraft but also the sequencing of traffic mix on the runway at any given point of time. Larger separation interval times are required by aircraft pairs with small aircraft in lead compared to other aircraft pairs.

The research also illustrates that by scheduling and sequencing flights in a certain sequence an increase of up to 27% in existing runway capacity may be achieved.

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The issue of future capacity of Changi airport in Singapore is currently the subject of much debate. Runway occupancy time is an important control parameter in enhancing the use of current infrastructure to increase capacity of existing runways. Due to land availability constraints in Singapore the construction of new runways is also limited. The realistic estimates of the effects of capacity enhancement are desirable, but these estimates are difficult. This research estimates the runway occupancy time and maximum runway capacity at Changi airport using AirTOp simulation software and Monte Carlo analysis.

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Chapter 1: Introduction

1.1 Background of the study

“For I dipped into the future, far as human eye can see,
Saw the vision of the world, and all the wonder that would be;
Saw the havens fill with commerce, argosies of magic sails,
Pilots of the purple twilight, dropping down with costly bales.” [27].

Air Transportation Management has gained a lot of importance in past two decades all over the world, be it in developed or in developing countries. As they say, the world is now a “global village”. The products manufactured in one part are transported to the other in a short span of time, assembled together and then the end product reaches the consumer. In this study the opportunities and issues facing air transportation management at Changi airport in Singapore have been investigated.

It is interesting to note that Air Transportation provides less than 3% of global volume of goods shipped but a huge 35% by value [41]. The air transport volume has increased more rapidly as compared to ocean or land transport volume. International Air Transport Association (IATA) and the World Bank have played important role in advancement and development of air transport industry.

The World Bank is also involved in ATM research [38], to analyze and deal with the critical issues that the world’s air transport industry is currently facing. It is making efforts to assist clients in establishing a safe, secure, cost efficient and reliable air transport network. The topics are regarding policy advice, master planning analysis, air carrier restructuring and privatization, energy, and capacity building for regulatory oversight, etc. Earlier, the World Bank has financed equipment such as aircraft for state-owned airlines, and infrastructure projects. With the liberalization of the air transport sector worldwide, and the privatization of many state-owned airlines, the World Bank has shifted its pure investment focus to a more policy and regulatory

support function. While the World Bank is still occasionally financing some large airport projects, such as Egypt's Terminal III, it has also engaged in financing private air carriers in developing countries. Over the years of bank operation, the air transport sector has provided various services to client countries, including air transport policy advice, sector analysis and master planning, capacity building for regulatory oversight, infrastructure investment for airports and air traffic control systems [38].

All countries of Europe have stepped up their tempo for effective ATM as the companies are growing wary of the recession and also they want to take up a lead. The single European sky ATM research, SESAR was launched in 2004 by the European Commission to reform European ATM [17]. The platform is set-up to develop a comprehensive strategy for research and innovation in air transport management in Europe. The mission of SESAR aims at bringing together all stakeholders, to collaborate and coordinate on future research and innovation priorities within the frame of next European R&D Programs, including the HORIZON 2020. It has been proposed to increase the overall efficiency, create additional capacity in the system and safety needs at an overall EU level [17].

After going through much of literature that is already present and also according to industry, a conclusion can be reached that there is no clear and univocal voice in the area of research and innovation on air transport management in Singapore and south east Asia, while there actually is a strong need for this. Moreover, it is clear that research and innovation could leverage more value to the industry. Apart from a lack of literature on runway capacity management in Singapore, the scope of current innovation roadmaps for capacity management is too narrow. There is a need for a view on capacity management in which everybody involved in air traffic management should collaborate closely to reach efficient operations.

Air Transportation in Singapore today faces a lot of challenges ahead. Apart from rising air fuel prices, Singapore faces the challenge of 'choking skies' i.e. air traffic congestion. The existing and new LCC (Low cost carrier) airlines would increase the flight numbers and lead to a gridlock and this increase will also cause the emissions to increase. With air travel in Asia set to grow by 5.7% per year [41], as estimated by

International Air Transport Association. Singapore will be the worst hit because of its strategic position in Asia Pacific region and the huge amount of air traffic. The civil aviation authority of Singapore needs to urgently address the situation. A key challenge is integration and exchange of information of air traffic technology and capabilities among the politically and economically diversified countries of Asia. Moreover, as a safety measure the region can push for common systems and procedures and also invest in technology to track aircraft movements. Aviation industry will continue to grow rapidly, which in turn means that global prices of air fuel will continue to rise. China is planning to develop 100 new airports by 2020, as per airport news [42]. However, still one of the greatest challenges faced by the aviation industry is dealing with the impacts of climate change due to increasing emissions and growing air pollution. There are almost 150 global airports identified as being at risk of sea level rise [44]. Temperatures are also predicted to rise by up to 4.4°C by 2099 due to climate change [43]. Higher temperatures affect aircraft lift, which means longer runways will be required for aircrafts to take off. For a country like Singapore, which has a small land area efforts must be made to utilize the airport capacity to its fullest. Figure 1 shows the density of traffic in Singapore Airspace.

Figure 1: Airline Traffic in Singapore Airspace [37].

Figure 2 shows the global airline traffic trends. It can be observed that Asia's growth is highest among all continents of the world and it also has 7 out of 10 busiest air traffic routes.

Figure 3 depicts the density of world air traffic over various countries. It can be seen that the density is very high over the United States. In Asia south east nations have the maximum density.

Figure 3: A snapshot of Density of world Air traffic [18].

1.2 Objective of the study

Airport capacity has become a major concern in today's air transportation environment, as the industry is growing globally. Although realistic estimates of the effects of capacity enhancement may be desirable, such estimates are difficult. Through the use of AirTOP and Monte Carlo simulation, this study quantifies and compares the relative capacity enhancements that may be carried out at Changi Airport in Singapore. In this study, the first objective was to get a close estimate of runway occupancy time and separation interval values between aircrafts. The second objective was to use the results of first objective in analysis of an additional 3rd runway and estimate the "unconstrained" capacity at Changi Airport.

Capacity constraints can increase costs both for airlines and to passengers, and longer delays can create passenger inconvenience. One approach to increase throughput is to expand airports with additional runways. However, the construction of new runways and opening of new airports does not only require large capital investment, but it is also limited by land availability, and it is subject to noise and environmental regulations.

Since the construction of new airports and new runways is limited, another approach is needed to accommodate air traffic growth. The other approach looks at the factors that limit runway throughput. The first factor is runway occupancy time and the second factor is wake vortex separation or the separation time interval between two aircrafts. In bad weather conditions, it is the air traffic controllers' responsibility to maintain required separations between arrivals. On good weather days, however, this responsibility is transferred to the pilots, who then decide on the appropriate spacing. This shift of responsibility to the pilots often leads to increased runway throughput due to smaller inter-arrival spacing, which shows that separation requirements could potentially be reduced when good weather conditions prevail. If wake vortex separation (separation time intervals) standards can be reduced without compromising safety, the reduced spacing is likely to have a positive impact on airport capacity.

1.3 Scope of the study

The scope of this study is to analyze data of 7 days, from 8th to 14th Sep 2014, which is approximately 6600 movements of arrivals and departures. By analyzing this data using AirTOp simulator a close estimate of the runway occupancy times (ROT) and separation intervals between different types of aircrafts at Changi airport was found.

The results of ROT and separation time intervals are discussed in section 3.3.2. These results not only help to identify the arrival pair cases where runway occupancy is the limiting factor in determining runway throughput, and the aircraft pairs for which, the separation interval is the restricting criteria but also these results were then fed to Monte Carlo simulation to estimate the unconstrained capacity of the existing 2 runways of the Changi airport. The Monte Carlo simulations are discussed in detail in Chapter 4.

This study with use of AirTOp and Monte Carlo simulation can help to quantify the potential runway throughput benefits of reduced wake separation time interval concepts.

Assumptions of this study:

- Unconstrained capacity and runway utilization at Changi Airport.
- Arrival Runways: 02C, 02L. Departure Runways: 20C and 20R [40].
- Focus is given to total number of movements and not specifically to number of arrivals and departures. Since the objective of this study is to estimate the unconstrained runway capacity.

Chapter 2: Literature Review

Runway occupancy time and capacity studies have been conducted in the past. A loss in wake vortex distance separation standards at Atlanta was reported in Haynie's (2002) study of inter-arrival time measurements [32]. Three days of operational data was collected under Visual Meteorological Conditions (VMC), which resulted in high uncertainty because of small sample size, especially when during occurrence of simultaneous approaches [32].

In USA a vast majority of aircraft surveillance is carried out by ground based radar systems. Dallas Fort Worth International Airport's (DFW) traffic flows were studied by Ballin and Erzberger (1996) [28] over a six month period with the help of radar systems. Radar tracks were recorded to measure landing separations and find out the rush time slots. Their results showed that to improve consistency and accuracy of time interval between arrivals on final approach leg, a large potential of improvement exists.

A landing time interval model based on ATC practices at Boston was developed by Venkatakrishnan et al. (1993). Their study analyzed the observational flight position data that was manually collected. Visual observation and manual data collection of airport operations is no longer used because of the modern systems. The new systems have a big range of features to analyze, and report air traffic data with better accuracy than the stopwatch measurements [12].

A variety of mathematical and computer simulation models have been developed to calculate runway capacity. Other probabilistic models like the queuing model have been used for estimating capacity of runways. The model was used by Blumstein [1] (1959) to estimate capacity when a runway is used solely for arrivals. The same queuing model was used to study departures and mixed movements by Odoni and de Neufville (2003) [31].

In their study of US airports, Lakatos and Tamas, the runway capacity constraints have been studied using Airport Surface Detection Equipment Model-X (ASDE-X) surveillance data. The study analyses runway occupancy times and wake vortex as

reasons for influencing the capacity of a runway. It evaluates the effects of reducing wake vortex separation for various types of aircrafts. Further, the study mentions that rapid exits reduce occupancy time and increase the capacity of runway more than the traditional 90 degree angled runway exits and size of aircraft does not necessary affect the occupancy times [26].

A study regarding capacity management and delay propagation was conducted by Pablo et. al, (2013) for US airports. They studied the performance of ATM capacity system in terms of delays. They introduced a model that reproduced delay patterns in the US. The results showed passenger and crew connectivity as the most relevant internal factor contributing to delay spreading and a very little risk of instability. Also, it was concluded that an important role is played by technical, operational or meteorological issues in capacity utilization [30].

In the paper by department of transport in UK, the future requirements of airports all over UK have been studied. The paper states to build new airports at a number of locations in UK to cater to the growing air transport demand. It also points out to make best use of existing airport capacity [15].

The director of air traffic management research institute (ATMRI), Mr. Hsin has also stressed upon the need to improve air traffic management in Asia and grow capacity. It has also been pointed out that a catastrophic gridlock may occur if work is not done in Asia about this [4].

An important study done by Hong et. al [36], about the operational efficiency of Asia Pacific airports evaluates the efficiency of Asia Pacific airports over a decade (2002 - 2011). The study involved a 2 stage method of Data Envelopment Analysis (DEA) to assess airport efficiency and regression analysis to identify the key determinants of airport efficiency. Their results indicated that Adelaide, Beijing, Brisbane, Hong Kong, Melbourne and Shenzhen as efficient airports. It also pointed out the factors that influence the efficiency of an airport namely, the percentage of international passengers handled by an airport, airport hinterland population size, dominant airlines and GDP per capita.

Multilateration is a technique of locating aircrafts accurately to apply a time spacing interval of arrivals. A number of ground stations are employed in this. Replies from transponders of the aircrafts are gathered by the ground stations, including radar and Automatic Dependent Surveillance Broadcast (ADS-B) avionics, and hence the aircraft position is found based on the time interval spacing of arrival of the signals for the aircraft. These systems have been installed at several airports already [45].

Data at Detroit Metropolitan Wayne County airport (DTW) was analyzed by Jeddi et al. (2006) to find the time and position of arrivals and departures. The probability distribution of flight arrival timings, landing time intervals, runway occupancy and simultaneous runway occupancy was derived from the analysis. The study revealed that a beta distribution and not a normal distribution represent the runway occupancy. In visual meteorological conditions (VMC) and instrumental meteorological conditions (IMC) conditions runway occupancy time is almost same [5].

Multilateration data was also studied by Levy et al. (2004) to get the probability distributions of inters arrival time and distance separations for a lot of arrivals at Memphis International Airport [6].

Runway capacity measurement is very important to determine and forecast any possible capacity changes in the long term for which the air traffic controllers might prepare. Measuring runway capacity is required to forecast any long term capacity changes. A lot of flow control methods may be used to reduce air traffic delays in case of reduced capacity to maintain optimal operational performance.

Capacity of any airport is also affected by the performance of the airlines at that airport. Hashem et. al, 2014 in their study presented a structural equation method (SEM) for estimating the performance of the airlines. They sampled 214 airlines for their study and their results indicated performance of the airlines based on the economic situation and internal operations of airlines [19]. The same SEM method was used by Yang et al. 2012 [25]; Chiou et. al, 2010 with respect to low cost airlines [54]. Hsu et. al 2012 [52], and Chang 2012 [53] studied the effects of cabin safety on airport capacity. The effects of traffic control on airport capacity were studied by Kuo et al.

2012 [9]. Other methods that have been used to study the factors affecting capacity of an airport are ANOVA [16], (Gilbert et. al, 2003), time series (Flouris et. al, 2004) [35], regression (Hung et. al 2005 [24] and Clougherty et. al 2009 [23]), data envelopment analysis (Barbot et al, 2008) [11], order preference technique (TOPSIS) (Feng et. al, 2000) [8], multiple criteria decision making (Hsu et. al 2013) [7] and structural equation modeling (Jenatabadi et. al, 2012) [20].

Software simulations and mathematical models have been developed to calculate runway capacity. In this study, a probabilistic (Monte Carlo) and an AirTOp simulation model is used as the basis for estimating capacity of Changi airport's runways. The mathematical probability model, Monte Carlo has been previously used by Daniel Irvine et al. (2014) [13] to estimate capacity of London airport and in south of England. Their study depicted the results of having new runways at various airports and also provided ways of increasing capacity by using existing runways in a different manner. Pitfield and Jerrard (1999) also used the same technique to estimate capacity of Rome Airport and analyze the concept of unconstrained capacity [14].

Chapter 3: Estimation of Runway Occupancy Time and Runway capacity at Changi Airport.

Terminal Maneuvering Area (TMA) is a circular region around the airport having a 50 - 60NM radius [29]. It is depicted in figure 4.

Figure 4: Terminal Maneuvering Area [29]

Various waypoint fixes are labeled as entry through which air traffic enters the TMA boundary. To handle the arrival/departure traffic in a better way, these waypoints are grouped together into 4 meter-gates. At each meter gate traffic coming from the en-route airspace is merged and flows into the TMA as a single stream [29]. In some cases, two streams which are not dependant are allowed to flow separately. These are of two primary aircraft types: jets and turboprops. For every stream a route is pre-

defined which leads to/from the runway. A series of fixed waypoints is known as a route. The path between two consecutive waypoints is known as a trajectory segment and when these segments are shared by more than two routes, it is known as merging. For any arrival or departure flight, the trajectory segments make up the path. This path can be represented by a series of time slots that are put together and form the flight's route. The estimated time of arrival, x and y coordinates, speed of aircraft, altitude and heading are there for each time slot. When an aircraft enters the TMA from its en route phase of flight, it can either be asked to wait in the holding area near entry gate depending on the traffic at the runway or may be asked by the airport ATC to proceed along a prescribed route to the arrival runway. All outgoing or incoming traffic from various streams flows along pre defined routes after being merged to some common waypoints. When the final approach fix (FAF) is reached all traffic allocated to the same runway for landing is merged before descending to the threshold of the runway. The merging procedure is ideally done at a distance of around 5NM before the threshold of the runway. One important point to note here is that once the traffic approach phase is started by the ATCs there can be no switching of positions of the aircraft streams that have been merged on the same designated route. This is because of the safety measures and wake vortex separation rules that are to be maintained between the aircrafts [29].

In case of departures a similar procedure is followed. The only difference being that air traffic flows from runway to the initial fix and then diverges along designated trajectory segments, thus exiting the exit gates of the TMA. The Terminal Maneuvering Area of any airport is the most congested part in all of its airspace. The air traffic in TMA is controlled by two types of controllers: the first being the Terminal Radar Approach Control (TRACON). This controls the traffic in 5NM to 50NM radius from the runway i.e. from the Initial Approach Fix to the Final Approach Fix (FAF). The second is the Air Traffic Control (ATC), which monitors and controls the air traffic from the final approach leg till the runway. The scheduling and sequencing of traffic is done either by a controller or a traffic management advisory system that follows the first come first serve (FCFS) rule [29]. The traffic is sequenced to land on

the runway in FCFS order based on its estimated time of arrival (ETA). The sequence that was originally made during stream merging must always be followed while completing the final approach leg to the runway, hence maintain safe distance and safety till the aircraft lands. When traffic management advisory is used, it may be that instead of FCFS rule the sequence of positions may be shifted, where the objective is to reduce delay and use runway capacity to its maximum.

3.1 Study of Changi Airport

The issue of Changi airport future capacity in Singapore is currently the subject of much debate. Although realistic estimates of the effects of capacity enhancement may be desirable, such estimates are difficult. Through the use of AirTOp software and Monte Carlo simulation, this study quantifies and compares the relative capacity enhancements that may be carried out at Changi including that of an additional runway and changes to operating practices.

Assumptions of study:

- Unconstrained capacity and runway utilization at Changi Airport.
- Arrival Runways: 02L, 02C. Departure Runways: 20C and 20R [40].
- Focus is given to movements and not specifically to arrivals and departures.

Unconstrained airport capacity is a concept that the IATA [46], International Air Transport Association put forward. It means “the capacity of an airport with a reservoir of traffic that is available always, and the use of all planned air traffic data and technological improvements to manage that traffic” [46]. To establish its value and utility in Singapore, the case of Changi Airport is studied in the following pages.

The Civil Aviation Authority of Singapore (CAAS) is closely engaged in capacity study of Changi Airport [39]. A new concept of capacity is defined [46] that might be used to plan and to draw conclusions by comparing real flow capacity and existing runway capacity, including those derived from simulation software, such as AirTOp, i.e. real flow totals and declared capacity. As per a CAAS study [34], the two existing runways can support up to 430,000 flights a year, if better utilized. The following pages outline the methodology that has been used to estimate values for “declared capacity”. The alternative scenarios depicting possible ways of runway usage can be categorized in 4 cases, which are:

Case 1 (Scenario 1). **Single operations** (only arrivals on one runway and only departures at the other runway).

Case 2 (Scenario 2). **Mixed mode operations** (arrival and departures can happen at the same runway)

Case 3 (Scenario 3). **Managed departure runway operation.**

Case 4 (Scenario 1). **Changi 3rd new runway scenario.**

These cases have been described in Chapter 4. The capacity definitions are outlined in section 3.2, including that of “Estimation of baseline capacity”. The section 3.3 describes the AirTOP simulation and its application that govern the Monte Carlo analysis. Chapter 5 outlines the results of simulations.

3.2 “Unconstrained” capacity definitions

There have been discussions [34] about the development and provision of future capacity of Changi airport. The issue has drawn opinions from those who claim connectivity to be a vital ingredient for economic growth and those who think that expansion of airports creates environmental and social burdens [39]. CAAS has evaluated a list of possible solutions [39]. The strategic location of Singapore may be taken into account while deciding and evaluating the Changi airport's capacity. Also, because of the small land area of Singapore, CAAS would like to have some realistic estimate of all the possible enhancements in capacity of Changi [39]. It should be taken care that the proposed new capacity decisions should be able to compare and reflect the real traffic conditions that exist. Otherwise all hypotheses get flawed.

Moreover, a number of factors exist that add to the difficulty in achievement of such real estimates. For example, if it is assumed that schedules of arrivals and departures are tightly followed while estimating the decisions of enhancing capacity, the full capacity of any airport would not get reflected. Also, it should be taken into account that realistic simulation of decisions taken by air traffic controllers is very difficult because they need to manage the arrival/departure traffic.

The basic idea behind unconstrained capacity [46] is the attempt to relate existing infrastructure with actual and possible air traffic movements very closely, so that existing infrastructure is better exploited without investing more time and resources. If the infrastructure that exists can be utilized in a better way, the huge investment in infrastructure may be postponed or be avoided.

CAAS is focusing on developing methodology to help in determining total capacity of Changi airport's layout so that future plans of expansion can be made [19]. This work is ongoing but it is expected that a new runway will be built by 2020 and a new mega terminal will be opened in the next decade making the capacity of Changi a whopping 135 million passengers per year [19]. Expansion is critical for Singapore to remain the premier air hub amid keen contest from other airports in countries such as Malaysia, Thailand, South Korea, and Hong Kong, to name a few [34].

As a first step this chapter describes the capacity definitions of declared capacity, sustained runway capacity and unconstrained runway capacity.

1. **Declared capacity** is defined as the capacity limit of an airport which is described in terms of aircraft movements in an hour [46] [14].

2. **Sustained runway capacity** is defined as the maximum sustainable throughput of the runway. In other words it is the flow rate that can be achieved when aircrafts operate under: instrument flight rules, a specific traffic mix (small, medium or heavy), weather conditions (ideal weather or turbulent rainfall), with a good air traffic management (ATM) and runway management system. Acceptable delay may be defined as the delay which may be accepted by the airlines that serve a particular airport, from perspective of aircraft utilization or of scheduled time table. The greater the delay, lower is the capacity and hence the availability of additional slots. This leads to reduced aircraft utilization and higher costs of operation that amount to approximately \$120/minute. There exists a point at which yield is exceeded by the costs over the period being studied. For example, at Heathrow airport the accepted delay is ten minutes, whereas in Amsterdam is 4 minutes. However, a rule of thumb used by IATA airlines is that the delay up to 10 min is acceptable by the airlines and the airport authorities [21] [22].

3. **Unconstrained runway capacity** is defined as the maximum throughput of the runway i.e. the flow rate which achieved ideally, without taking into account the level of service but with the safety requirements being met [46].

For simplicity of the study of estimating unconstrained capacity, single runway operations have been considered i.e. one side of runway is used for arrival and the other for departures. The arrival process starts from the destination airport. Air traffic controller staff starts sequencing flights that have to arrive long before they reach the terminal area. Once aircraft reaches the final approach leg, the wake vortex separation [47] [14] requirements are enforced and runway occupancy time (ROT) plays a major

role in determining when the next landing can take place. The capacity of runways is also influenced by other factors, which are depicted in figure 5.

Factors influencing runway capacity

Figure 5: Runway capacity factors [13].

Wake vortex is an important reason affecting the runway capacity. It is an unavoidable by product of aerodynamic lift. The reason [47] for this is that when the low pressure air above the wing surface comes in contact with the high pressure air under the wing surface at the wing tip, a swirling mass of airflow is generated because of the pressure difference as shown in figure 6.

Figure 6: Wake vortex generated by an aircraft [10].

The strength of the wake vortices is a function of the weight of the aircraft, the speed with which it flies, and the profiling of the wing. Thus, a large aircraft generates stronger wake vortices than medium or small aircraft. A wake vortex encounter can occur when an aircraft follows a large or heavy aircraft too closely. This is a potential hazard for aircrafts since it can lead to a complete loss of control and loss of lives [47] [48]. In order to minimize risks such as these the separation distances have been defined by ICAO [21].

The aircrafts are put into wake groups, such as heavy (A380, B747), large, and small (E120), based on their maximum takeoff weight (MTOW) measured in lbs. Table 1 shows the weight criterion followed by FAA [47].

	Heavy	Large	Small
MTOW (lbs)	MTOW $\geq$ 300,000	41,000 < MTOW < 300,000	MTOW $\leq$ 41,000

Table 1: Aircraft wake categories based on MTOW [47] [26]

Table 2 shows the estimated runway approach speeds of different aircraft based on airport surface detection equipment mode (ASDE) aircraft surveillance data.

Aircraft	Average Threshold Speed (knots)	Estimated Final Approach Speed (knots)
Small	109.1	110
Lower Medium	125.7	130
B757	136.8	140
Heavy	145.3	150

Table 2: Estimated approach speeds based on Airport Surface Detection Equipment Model (ASDE) aircraft surveillance data [26].

The high speed runway exits can make a significant difference in runway occupancy. As per ICAO standard guidelines while designing a high speed exit, the intersection angle of a rapid exit taxiway with the runway should not be greater than 45° and not less than 25° . The preferable angle is 30° [21].

Figure 7 shows a rapid exit taxi way.

Figure 7: Standard (A), Rapid (B) runway exits [26].

Previously, when simulation modeling has been used by airports to assess capacity of runways, the variables that have been used are based on standards defined by the performance criteria of the pilots noted at that particular airport and by ATC. However, the model doesn't utilize all ATC and Air traffic management procedures and to maximize the capacity. The model of unconstrained capacity discussed, tries to incorporate maximum procedures possible, so that airlines and the airport authorities can determine the procedures and improvements in their infrastructure.

3.3 AirTop Simulation

In this section the method which is employed to determine Runway occupancy time at Changi airport i.e. AirTop simulator software is introduced and results of analysis are explained to provide estimations of the relative effect on airport capacity.

AirTop (Air Traffic Optimization) is new generation gate-to-gate fast time simulation software [49]. Some of its features are:

1. Unique rule-based gate-to-gate fast-time simulator with features including [49]:
 - En-route traffic & ATC modeling
 - Advanced Airport TMA/TRACON modeling
 - Realistic airport ground movements
 - 4D Trajectory Based Operations and Air Traffic Flow Management (ATFM) modeling.
2. Multi-agent based modeling which [49]
 - Captures controller roles, tasks (ATC and airport controllers, flow managers, airport authorities, aircraft operator centers, etc)
 - Gives accurate and customizable measure of controller workload demand.
3. Integrated table and map-based application that helps in [49].
 - Scenario editing, project check & debug, simulation run and playback, reporting all in one single application
4. Integrated reporting [49].
5. Open, modular and extensible [49].
Reduces operational costs and enhancement delays [49].

Monte Carlo [50] simulation on the other hand is a randomized algorithm whose running time is deterministic, in this report the running time of the simulation has been taken as 1 hour. The output of the simulation might be greater than the actual value because of queuing and it lies within a certain (typically small) range.

Monte Carlo analysis is a powerful tool to sample data from distributions that are cumulative and helps to achieve steady state results [50].

3.3.1 Estimation of traffic mix and its probability at Changi Airport

In the study analyzed in this report, the variables are the traffic mix and the order in which arrival or departure occurs. The composition of simulated traffic mix is derived from the actual traffic mix at Changi in peak hour of 7 days of September 2014. The total traffic data of arrivals and departures that was analyzed was from 00:00 AM till 23:59 PM for 7 days, from 8th to 14th Sep 2014.

The total number of flights, including both arrivals and departures, for these 7 days was approximately 6600. This can be averaged out to 943 movements daily for the 7 days.

After analysis of total movements (arrivals and departures) the peak hour was identified as 8 PM – 9 PM for all 7 days. In the peak hour, the total number of arrivals and departures was found to be 64 for 12th Sep 2014, the day being a Friday. Also the total number movements was recorded as 1067 for 12th Sep 2014, which is more than the average movements of 943 approximately on all days. The data of flights on 12th Sep 2104 is depicted in figure 8. The data of 6600 movements, used for analysis, was downloaded from Changi Airport Group [39] website.

Figure 8: Total traffic movements (arrivals + departures) per hour.

Figure 8 depicts the “peak hour” of 12th Sep 2014. In the peak hour there were 64 movements and it occurred between 8PM to 9PM.

After identifying the “peak hour”, the traffic mix of aircrafts was found by researching data for the all the 6600 flights to know whether the aircraft fell under the category of heavy, medium or small.

After the research the average traffic mix for peak hour of 7 days was found to be approximately 1% Small, 56% Medium and 43% Heavy aircrafts.

Figure 9 depicts the breakdown of traffic mix at Changi for “peak hour” of 7 days.

Figure 9: Traffic mix at the Changi.

After getting the values of traffic mix, the corresponding probabilities of whether the arriving or departing aircraft will be a small, medium or heavy were found. The probabilities are shown in table 3. These probabilities will be used in Monte Carlo simulations described in Chapter 4.

Probability Of Arriving/Departing Aircraft	Type Of Aircraft
0.43 to 1	Medium
0.01 to 0.43	Heavy
0 to 0.01	Small

Table 3: Probability of arriving or departing aircrafts

The probabilities mentioned, influence the arrival and departure separations, which are governed by ICAO rules [21] [22]. UK Nats inputs for separation times were also considered. The table 4 depicts the ICAO rules for separation times in case of arrivals. Table 5 depicts the separation rules for departing aircrafts.

Separation times for **Arriving aircraft** (in minutes).

	Following aircraft			
Preceding aircraft		Heavy (H)	Medium (M)	Small (S)
Heavy (H)		1.78	2.22	3.96
Medium (M)		1.11	1.78	3.4
Small (S)		1.11	1.11	2.2

Table 4: ICAO and UK NATS arrival and separation rules [21] [22].

Separation times for **departing aircraft** (in minutes).

	Following aircraft			
Preceding aircraft		Heavy (H)	Medium (M)	Small (S)
Heavy (H)		2.67	3.11	4.53
Medium (M)		1.11	1.78	3.4
Small (S)		1.26	1.26	2.2

Table 5: ICAO and UK NATS departure and separation rules [21] [22].

3.3.2 Estimation of Runway occupancy time (ROT) and Separation time intervals between aircrafts using AirTop

Runway occupancy times (ROT) as well as the separation time intervals between arriving aircrafts were analyzed by simulating the model of Changi airport on AirTop. Figure 11 shows the simulated model of Changi airport on AirTop.

The observations were recorded for all 9 possible combinations between heavy, large and small aircrafts. The 9 combinations for which data was recorded were:

- Heavy aircraft is leading, Heavy aircraft follows it.
- Heavy aircraft is leading, Medium aircraft follows it.
- Heavy aircraft is leading, Small aircraft follows it.
- Medium aircraft is leading, Heavy aircraft follows it.
- Medium aircraft is leading, Small aircraft follows it.
- Medium aircraft is leading, Heavy aircraft follows it.
- Small aircraft is leading, Heavy aircraft follows it.
- Small aircraft is leading, Medium aircraft follows it.
- Small aircraft is leading, Small aircraft follows it.

The model of Changi airport was simulated on AirTOp. Effort was made to keep the simulated model as close as possible to the actual layout of Changi. The latitude and longitudes of runways were plotted in accordance to the actual ones.

The document [51] for aeronautical information services from CAAS was referred for plotting the runway longitude and latitude for the runways. The same document [51] was used to get the aircraft parking position coordinates.

The simulated model is shown in figure 10. The parking positions and they taxiways can be seen in figure 10.

Figure 10: Simulated model of Changi on AirTOp.

After the model of the airport was simulated, the data of all the movements, was entered into the AirTOP model to have a good estimate of the runway occupancy time as well as separation time for each pair of arriving and departing aircraft. This holistic method enabled to fully simulate the operations at Changi airport runways and get a good estimate of separation time and ROT for each aircraft category. The data which was entered in the AirTOP model consisted of the flight arrival time, departure time and the type of aircraft (heavy, medium or small).

The simulation started at time $t = 0$. The first arrival can be seen in figure 11. It is to be noted that the time runway occupancy time measurement starts from the time when this arrival crosses the runway threshold. The parking positions and the two runways can also be seen in figure 11.

Figure 11: Arrival on the AirTOP simulation.

Figure 13 depicts the moment at which the minimum required separation time between two arrivals is fulfilled and the second arrival is allowed to land on runway 2. It can be observed from figure 13 that when the second arrival lands on the runway the first arrival flight at that time has already crossed the runway threshold and is on the taxiway segment of the runway. So the runway occupancy time for the first arrival flight is the time spent by it on the runway, which is the difference between the time when it exits the runway threshold and the time when it enters the runway threshold. In a similar manner the runway occupancy time measurement for flight 2 starts when it crosses the threshold of the runway and ends when it exits the runway.

Figure 13: First arrival reaching the taxiway segment of the AirTop simulated model.

Figure 14 shows that moment in the simulation when it has reached its half way stage. The parking positions being filled up by the arriving flights can be observed. The details about the flights can also be seen. To illustrate, the details of the flight on left hand side can be observed to notice that the speed of aircraft before it takes the rapid exit way is 78 knots. The flight name is 9VSWA and so on. It also shows the category of aircraft and the aircrafts on runway and taxiway segments. The rapid exit taxiway segments can also be observed in figure 14.

Figure 14: Close-up of the Simulated Changi airport model.

Figure 15 shows the moment when first departure takes place from runway 1. The procedure is similar for calculating the separation time and runway occupancy time for the departing aircrafts. The ROT and separation time for each category of aircrafts are noted manually to estimate the minimum, maximum, mean and median. The estimates are depicted in table 15. Once the simulation gets over for all the flights, the data recorded for separation time intervals and ROT is analyzed further.

Figure 15: Departure from a runway.

From the breakdown of traffic mix in figure 9, it is evident that the majority of movements are of medium (56%) and heavy (43%) aircrafts at Changi. Hence, the ROT and separation time intervals are mainly governed by medium and heavy aircraft movements.

Also, the separation time and ROT had to be noted manually from AirTOP, and given the large amount of data of 7 days of operation, the data for all combinations of heavy and medium aircraft pairs was noted from the “peak hour” of operation to get a close estimate of ROT and separation interval time. It was kept to a limit of 200 flight pairs in “peak hour” (for each combination) for analysis, thus giving a good estimate of ROT and separation time intervals between aircraft types rather than just measuring the expected value of ROT and separation time.

In case of small aircrafts the data consisted of only 66 small aircrafts, since they just make up only 1% of the total traffic data that was analyzed for 6600 flights as depicted in figure 9. Hence, the limit of all combinations of small, medium and heavy pairs was by default 66.

Runway occupancy times (ROT) as well as the separation time intervals of arriving aircrafts were analyzed by simulating the model of Changi airport on AirTOP. The unit of measurement was kept as 'seconds' for both occupancy time and landing time separations. Table 6 shows the data of recorded values for ROT and separation times when a heavy aircraft is followed by a heavy aircraft.

In table 6, the first column is ROT when a heavy aircraft leads a heavy aircraft. The second column “Frequency” is the number of heavy and heavy pairs that took that value. To illustrate, 3 heavy - heavy aircraft pairs took 40 seconds of runway occupancy time. Similarly, 5 aircrafts took 41.5 seconds.

The 3rd column is the separation time between aircrafts that was recorded from AirTOp. Separation time is kept between flights to reduce the risk of wake vortex accidents. As per table 6, separation time of 100 seconds was recorded between 5 heavy - heavy pairs.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
40	3	100	5
41.5	5	103.5	16
43	11	107	17
44.5	8	110.5	13
46	16	114	23
52.8	24	117.5	25
54.3	20	121	20
55.8	18	124.5	17
57.3	19	128	16
58.8	11	131.5	9
60.3	16	135	12
61.8	18	138.5	7
63.3	8	142	9
64.8	11	145.5	5
66.3	3	149	3
67.8	2	152.5	1
72.4	4	156	1
86	3	159.5	1

Table 6: AirTOp simulated data of ROT and Separation Intervals between Heavy pairs

The distribution of ROT and separation time for 200 heavy - heavy pairs is shown in figure 16. The graph in red color on left hand side depicts the runway occupancy time recorded for the scenario when heavy aircraft is followed by another heavy aircraft.

On the other hand the graph in green color on right hand side in figure 16 depicts the separation interval between the two arriving aircraft. The time is measured from the instant when the first aircraft crosses the threshold of the runway till the following aircraft finishes crossing the threshold of the runway. The data depicted is captured using the AirTop simulator.

Figure 16: Runway Occupancy Times and Separation Times for Heavy Pairs.

As per figure 16 the ROT for maximum number of heavy pairs was 52.8 seconds. The separation time for maximum number of heavy and heavy pairs was approximately 117.5 seconds and on the other hand the runway was occupied for a minimum of 40 seconds and a maximum of 86 seconds, when a heavy aircraft was followed by a heavy one. The minimum separation time was 100 seconds and maximum was 159.5 seconds.

In a similar manner, table 7 and figure 17 depict the runway occupancy time and separation times for the scenario when a heavy aircraft was followed by a medium aircraft. The separation time for maximum number of heavy and medium pairs was approximately 141.3 seconds and on the other hand the runway was occupied for a period of 53.8 seconds by maximum number of aircrafts, as shown in figure 17. The runway was occupied for a minimum of 40 seconds and a maximum of 92 seconds, when a heavy aircraft was followed by a medium one.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
40	3	140	24
41.5	5	141.3	36
43.8	11	144.5	30
44.5	8	146.2	32
46.6	16	148.5	20
53.8	24	151.7	15
54.3	20	152.5	12
55.8	18	154.2	9
57.3	19	156.3	7
58.8	11	158.5	5
60.9	16	160.2	2
61.8	18	162.5	1
63.9	8	164.6	3
64.8	11	166.3	2
66.3	3	168.1	0
67.8	2	170.5	1
79.3	4	172.5	0
92	3	174.5	1

Table 7: AirTOP simulated data of ROT and Separation Intervals between Heavy Medium pairs

Figure 17: Runway Occupancy Times and Separation Times for Heavy Medium Pairs.

Compared to figure 16 an increase in occupancy as well as separation time was observed in the results of figure 17. The separation time for maximum number of heavy and medium pairs was approximately 141.3 seconds and on the other hand the runway was occupied for a period of 53.8 seconds by maximum number of aircrafts. The minimum value of separation time was 140 seconds. The maximum separation time for Heavy medium pairs is 174.5 seconds in table 7 compared to 159.5 seconds in table 6. This increase can be attributed to the fact that the wake vortex generated by a leading aircraft, which is heavy is strong and hence a medium aircraft has to wait more so that the vortex becomes weak and the medium aircraft is not affected by it.

Table 8 and figure 18 depict the runway occupancy time and separation times for the scenario when a heavy aircraft was followed by a small aircraft. The separation time for maximum number of heavy and small pairs was approximately 201.2 seconds and on the other hand the runway was occupied for a period of 73.3 seconds by maximum number of aircrafts as shown in figure 18. The runway was occupied for a minimum of 42 seconds and a maximum of 100 seconds, when a heavy aircraft was followed by a small one.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
42	1	190	4
43.5	2	192.8	6
45	2	195.6	5
46.5	3	198.4	5
55.8	7	201.2	8
59.3	7	204	6
62.8	8	206.8	5
66.3	5	209.6	6
69.8	7	212.4	4
73.3	11	215.2	3
76.8	4	218	1
80.3	3	220.8	4
83.8	1	223.6	2
87.3	2	226.4	3
90.8	1	229.2	2
100	2	232	2

Table 8: AirTOp simulated data of ROT and Separation Intervals between Heavy Small pairs

Figure 18: Runway Occupancy Times and Separation Times for Heavy Small Pairs.

Compared to figure 17 an increase in separation time was observed in the results of figure 18. The minimum value of separation time was 190 seconds while the maximum value was 232 seconds compared to 174.5 seconds in figure 17. The median value of separation time that was recorded was 201.2 seconds. This can be attributed to the fact that the wake vortex generated by a leading aircraft, which is heavy is strong and hence a small aircraft has to wait more so that the vortex becomes weak and the small aircraft is not affected by it. Also, From figure 18, it can be observed that there is a large gap between the maximum ROT and minimum separation interval time. Thus, lowering required minimum separations (assuming safety is maintained) can lead to additional runway capacity utilization and hence increase in throughput can be achieved.

Thus, it can be observed from figures 16, 17 and 18 that when heavy aircraft is the leading aircraft the separation times increase from 159.5 seconds, in case when heavy is followed by heavy aircraft to 232 seconds when a small aircraft follows a heavy aircraft.

Table 9 and figure 19 depict the runway occupancy time and separation times for the scenario when a medium aircraft was followed by a heavy aircraft. The separation time for maximum number of medium and heavy pairs was approximately 72.2 seconds and on the other hand the runway was occupied for a period of 42.4 seconds by maximum number of flights as shown in figure 20. The minimum ROT was 30 seconds while maximum was 66.4 seconds. Similarly, the minimum separation time was 69.2 seconds while the maximum was 103.2 seconds.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
30	15	69.2	13
34	18	72.2	33
38	28	76	24
42.4	40	78.7	27
46.4	32	82.2	23
50.4	34	85.7	20
54.4	10	88.8	16
58.4	10	92.3	18
62.4	8	95.6	15
66.4	5	103.2	11

Table 9: AirTOp simulated data of ROT and Separation Intervals between Medium Heavy pairs

Figure 19: Runway Occupancy Times and Separation Times for Medium Heavy Pairs.

Compared to figure 18 a decrease in occupancy as well as separation time was observed in the results of figure 19. This can be attributed to the fact that the wake vortex generated by a leading aircraft, which is medium, is not as strong as compared to a heavy one and hence a heavy aircraft does not have to wait more for the vortex to become weak, hence the decrease in ROT and separation time intervals. Also, it can be observed that the spread of separation time is starts very close to ROT measurements. The separation intervals cannot be reduced otherwise two flights will be on the runway at same point of time. Thus ROT is limiting the runway capacity throughput.

Table 10 and figure 20 depict the runway occupancy time and separation times for the scenario when a medium aircraft was followed by a medium aircraft. The separation time for maximum number of medium and medium pairs was approximately 90 seconds and on the other hand the runway was occupied for 51.3 seconds by maximum number of flights as shown in figure 20. The minimum ROT was 30 seconds while maximum was 68.5 seconds. Similarly, the minimum separation time was 80 seconds while the maximum was 124.3 seconds.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
30	10	80	17
34.1	7	85.1	12
38.4	10	90	28
42.7	18	94.9	19
47	25	100	25
51.3	39	104.8	19
55.6	36	109.3	21
59.9	30	114.5	20
64.2	17	119.4	21
68.5	8	124.3	18

Table 10: AirTOp simulated data of ROT and Separation Intervals between Medium pairs

Figure 20: Runway Occupancy and Separation Times for Medium Pairs.

Compared to figure 19 an increase in occupancy time was observed. On the other hand there was a small increment in separation time that was observed in the results of figure 20. This can be attributed to the fact that the wake vortex generated by a leading aircraft, which is medium, is not so strong and hence a medium aircraft that follows does not have to wait more for the vortex to become weak. If the required separation intervals for medium pairs is reduced, it can bring separations too close to runway occupancy, thus there is little potential to reduce the required minimum separation in this case.

Table 11 and figure 21 depict the runway occupancy time and separation times for the scenario when a medium aircraft was followed by a small aircraft. The separation time for maximum number of medium and small pairs was approximately 138 seconds and on the other hand the runway was occupied for 63.1 seconds by maximum number of flights as shown in figure 21. The minimum ROT was 30 seconds while maximum was 72.7 seconds. Similarly, the minimum separation time was 130 seconds while the maximum was 166 seconds.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
30	3	130	2
34.8	4	134	5
39.6	6	138	14
44.4	4	142	12
49.2	12	146	8
53.5	6	150	5
58.3	9	154	6
63.1	14	158	9
67.9	5	162	3
72.7	3	166	2

Table 11: AirTOp simulated data of ROT and Separation Intervals between Medium Small pairs

Figure 21: Runway Occupancy Times and Separation Times for Medium Small Pairs.

Compared to figure 20 an increase in runway occupancy and separation time was observed in the results of figure 21. This can be attributed to the fact that the wake vortex generated by a leading aircraft, which is medium is strong and hence a small aircraft has to wait more so that the vortex becomes weak and the small aircraft is not affected by it.

From figure 21, it can be observed that there is a large gap between the maximum ROT and minimum separation interval time. In this case, separation time interval is the limiting element for additional runway capacity utilization and throughput. Additional capacity can be gained by reducing the separation intervals.

Table 12 and figure 22 depict the runway occupancy time and separation times for the scenario when a small aircraft was followed by a heavy aircraft. The separation time for maximum number of small and heavy pairs was approximately 99.1 seconds and on the other hand the runway was occupied for 41 seconds by maximum number of flights as shown in figure 22. The minimum ROT was 5 seconds while maximum was 61.7 seconds. Similarly, the minimum separation time was 65 seconds while the maximum was 116.9 seconds.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
5	2	65	2
10.2	3	70.1	3
15.3	5	75.5	2
20.5	6	80.3	3
25.7	9	85	5
30.9	8	89.7	7
35.8	9	94.4	6
41	14	99.1	13
46.2	5	102.8	6
51.3	3	107.5	3
56.5	1	112.2	9
61.7	1	116.9	7

Table 12: AirTOP simulated data of ROT and Separation Intervals between Small Heavy pairs.

Figure 22: Runway Occupancy Times and Separation Times for Small Heavy Pairs.

Compared to figure 21 a decrease in occupancy as well as separation time was observed in the results of figure 22. This can be attributed to the fact that the wake vortex generated by a leading aircraft, which is small, is not as strong as compared to a heavy one and hence a heavy aircraft does not have to wait more for the vortex to become weak.

From table 12 and figure 22, it can be seen the ROT time values are too close to separation intervals for small leading and heavy following flight pairs. In some cases it might be that ROT exceed separation interval time if air traffic controls are not careful. It also means that for this case highest capacity of runway is achieved in peak hour. Also, a built in buffer is necessary to minimize go-around likelihood. “Go-around” means that the “following” aircraft has to “go-around” in the airspace in a loop to achieve required separation interval between flights. Thus, sometimes leading to high value of separation interval time. Hence,, throughput might be lost if “go-around” occur frequently.

Table 13 and figure 23 depict the runway occupancy time and separation times for the scenario when a small aircraft was followed by a medium aircraft. The separation time for maximum number of small and medium pairs was approximately 105 seconds and on the other hand the runway was occupied for 36.8 seconds by maximum number of flights as shown in figure 23. The minimum ROT was 5 seconds while maximum was 62.6 seconds. Similarly, the minimum separation time was 66.3 seconds while the maximum was 124.2 seconds.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
5	2	66.3	1
10.9	3	72.1	3
16.1	4	77.9	7
20.8	7	83.7	11
27.2	12	89.5	9
32.1	5	95.3	7
36.8	13	100.2	5
42.6	11	105	14
47.6	4	109.8	3
52.5	3	114.6	1
57.9	1	119.4	3
62.6	1	124.2	2

Table 13: AirTop simulated data of ROT and Separation Intervals between Small Medium pairs.

Figure 23: Runway Occupancy Times and Separation Times for Small Medium Pairs.

Compared to figure 22 a small decrease in occupancy time was observed whereas separation time increased by a small amount of 8 seconds approximately, in the results of figure 23. This can be attributed to the fact that the wake vortex generated by a leading aircraft, which is small, is not as strong as compared to a medium or a heavy one and hence a heavy or a medium aircraft does not have to wait more for the vortex to become weak. But the medium aircraft has to wait a bit more compared to the heavy aircraft.

Table 14 and figure 24 depict the runway occupancy time and separation times for the scenario when a small aircraft was followed by a small aircraft. The separation time for maximum number of small pairs was approximately 109.6 seconds and on the other hand the runway was occupied for 31.6 seconds by maximum number of flights as shown in figure 24. The minimum ROT was 5.1 seconds while maximum was 64.3 seconds. Similarly, the minimum separation time was 90 seconds while the maximum was 144.3 seconds.

Runway Occupancy Time (sec)	Frequency (No of aircrafts taking this value of ROT)	Separation Time (sec)	Frequency
5.1	2	90	2
9.3	1	94.9	3
16.1	4	99.6	5
21.5	6	104.7	7
26.8	10	109.6	13
31.6	15	114.4	12
37.8	12	118.7	5
43.1	7	123.6	7
48.4	4	128.9	3
53.7	3	133.7	5
59	1	139.4	3
64.3	1	144.3	1

Table 14: AirTop simulated data of ROT and Separation Intervals between Small pairs.

Figure 24: Runway Occupancy Times and Separation Times for Small Pairs.

Compared to figure 23, a decrease in occupancy time was observed whereas separation time increased in the results of figure 24. This can be attributed to the fact that the wake vortex generated by a leading aircraft, which is small, is strong enough for a small aircraft that follows, which has to wait for the vortex to become weak.

From figures 22 to 24 it can be observed that the ROT taken by maximum number of aircraft pairs gradually decreases from 41 seconds (between small – heavy pairs) to 31.6 seconds (between small – small pairs). The reason being the size and weight of aircraft. Heavier the aircraft, more time it needs to exit the runway and to slow down its speed. Whereas the small and light aircrafts can quickly slow down and are able to vacate the runway quickly.

The separation time intervals on the other hand follow an increasing trend in figures 22 to 24. This is because the wake vortex generated by a leading aircraft, which is small, is not as strong as compared to a medium or a heavy one. Whereas when a small aircraft is following it has to wait more than when medium or heavy follow a small aircraft.

Table 15 summarizes the ROT results for each aircraft type, after analyzing all the combinations of small, medium (or large) and heavy aircrafts using AirTop. It depicts the minimum, maximum, mean and median values of runway occupancy times for all aircraft types. To illustrate the results, if the minimum ROT value of a small aircraft is seen in table 15, it is 5 seconds. This is probably the case when small is the leading aircraft and exits through a rapid exit taxiway. On the other the maximum ROT value for a small aircraft is 100 seconds. This is probably one of the case when a heavy aircraft is the leading aircraft and small aircraft follows it. Similar is the case for medium and heavy aircrafts. The minima of ROT is recorded when the aircraft is leading and maxima is recorded when it follows a heavier aircraft than itself.

Count	Aircraft type	Minimum	Max	Mean	Median
1	Small	5	100	32.4	31.6
2	Large/Medium	30	92	42.5	42.4
3	Heavy	40	86	53.6	52.8

Table 15: Minima, maxima, median, mean of Runway Occupancy Times (ROT) (in seconds) of various aircrafts as per the data from AirTop.

Note: 32.4 sec = 0.50 min, 42.5 sec = 0.67 min, 53.6 Sec = 0.83 min

Figure 25 shows the mean and median of runway occupancy times as a function of aircraft size that was recorded through AirTop.

The mean values for small, medium and heavy were recorded as 32.4 seconds, 42.5 seconds and 53.6 seconds. Whereas, the median values for small, medium and heavy were 31.6, 42.4 and 52.8 respectively.

Figure 25: ROT mean and median as a function of aircraft size

3.3.3 Implications of AirTop simulations for ROT and separation times.

The AirTop simulations provide details on how much of separation time intervals do air traffic controllers apply on final approach at Changi airport. The figures 16 to 25 depict how the observed separations compare to runway occupancy. The results in section 3.3.2 help to identify the arrival pair cases where runway occupancy is the limiting factor in determining runway throughput, and the aircraft pairs for which, the separation interval is the restricting criteria.

For "medium aircraft" leading and "heavy aircraft" following pairs, and for all combinations where small aircraft is the leading aircraft, ROT limits the runway throughput because the wake vortex of the leading aircraft (which is lighter than the one that follows it) is not so strong. Thus, high separation time intervals are not required when a heavier aircraft follows a smaller aircraft than itself. Since the heavier aircraft doesn't have to wait much, it makes ROT as the limiting factor. When ROT is the limiting factor, additional arrival movements can only be accommodated if aircraft exit the runways sooner, which can be accomplished by familiarizing pilots with the existing runway exit locations and including runway exit descriptions in the flight planning process.

For medium and medium aircraft pairs, there is very little room to reduce separation minimums, and very little room to fly aircraft closer to the minimums. However, reducing the variation in the system and flying aircraft closer to the required minimum separation can provide additional runway capacity benefits.

For all other aircraft pairs, separation time interval is the limiting element for additional runway capacity throughput. This is because of the strong wake vortices generated by "leading" heavier aircrafts being so strong that "following" lighter aircrafts have to wait. If reducing separation requirements does not sacrifice safety standards, the reduction in required minimum separations would likely lead to an increase in runway utilization. In addition to reducing the gap between observed and

required minimum separations, runway throughput can also be gained by reducing the variation in the separations.

The results indicate that small aircrafts have the lowest ROT and heavy aircrafts have a high ROT as depicted in table 15. This is because of the arrival speed and the weight of the heavy aircrafts. The separation time interval depends on the 9 combinations described in section 3.3.2. While the combination of "heavy leading and small following" needs the maximum separation time because of the wake vortex generated by the heavy aircraft. The combination of "small leading and heavy following" needs the least separation interval because the wake vortex generated by small aircraft is not so strong and thus the heavy aircraft which follows it doesn't have to wait.

In addition to reducing the gap between observed and required minimum separations, runway throughput can also be gained by reducing the variation in the values of ROT. If the results of table 15 are seen there is a considerable difference between the maximum and minimum values for all aircraft types. If ROT and separation times are more consistent and are closer to the mean, the runway throughput benefits can be significant for Changi.

By knowing these results the air traffic controllers can be encouraged to separate aircraft as close to the minimums as plausible, and it can encourage pilots to exit the runway as soon as they are able to do so. Thus, increasing the utilization of the runways at Changi.

Figure 26 depicts the layout and proposed expansion of Changi Airport [34]. It shows the existing runways and also the proposed runway 3, which is estimated to be ready by 2020 [34]. The scenario of increase in runway capacity after 3rd runway is made operational at Changi is also analyzed using Monte Carlo analysis in section 4.4.

Figure 26: Changi Airport Layout [34].

The Monte Carlo technique has been used for analysis of all the scenarios. These scenarios are:

For case 1 (Scenario 1), single operations (only arrivals on one runway and only departures at the other runway), it is assumed that there are only arrivals on 02C since it is located closer to the residential areas [39]. Likewise, the runway 20R is used only for departures. This logic [39] is premised on the fact that departures are noisier than the landings. Also, it is to be noted that independent instrument runway operations are permitted on 02C and 20R, as per ICAO rules since the runways are greater than 1.8 km apart [2].

For case 2 (Scenario 2), mixed mode operations, arrivals take place on 02C and 02L and departures are there on 20C and 20R. Also, for this case, since the departures are to be slotted in the time gaps between arrivals, it is assumed that all the departures take maximum runway occupation time of 0.83 minutes (53.6 seconds), which is shown in table 15.

Finally in case 3 (Scenario 3), there are arrivals on 02C and 02L. “Managed departures” are on 20C and 20L. “Managed departures” mean that medium weight aircrafts take off from 20C, with heavy and small aircrafts departing from runway 20R. Thus, reducing dependency between departures of heavy, medium and small aircrafts on those runways. Also, for this case, since the departures are to be slotted in the time gaps between arrivals, it is assumed that all the departures take maximum runway occupation time of 0.83 minutes or (53.6 seconds), as shown in table 15.

Chapter 4: Monte Carlo Simulations for estimating capacity and Data Tables

Arrival-departures have been simulated during peak period of movements for each runway. The time has been taken as 1 hour. The separations are governed by the results of AirTop simulation and the International Civil Aviation Organization (ICAO) rules [21].

It is important to note that in this study the simulations for each scenario have been repeated 10 times so that steady state results are achieved before “peak hour” simulation. The Appendix shows the samples of the 10 repetitions that were done for arrivals and departures on various runways. The tables 16 to 28 depict the results of “peak hour” simulations.

The first step is to define the random variables. In the case analyzed here, it is the traffic mix at Changi airport. Incoming and outbound aircrafts are separated according to size because of the wake vortices that are created. Larger aircraft create more wake vortex than smaller aircraft and hence every aircraft is assigned to a wake turbulence category to ensure safe separation. The traffic mix thus directly influences the capacity.

It is to be noted that the separation distances are different for same type of aircrafts depending on whether the movement is an arrival or departure. This is because of greater air vortices generated during departures as compared to arrivals [21].

An important assumption is that all aircrafts are travelling at an average speed between 170 to 175 knots. This is based on the premise that the speed at the outer marker of the airport, as directed by ICAO [21], is between 150 to 180 knots. The speed of an aircraft's final approach depends on a lot of factors that include weight, weather conditions and airport's local operating requirements. Therefore, in order to convert wake turbulence categories to approach speeds, a number of assumptions were made by ICAO [21]. These included identifying the approach speeds of specific aircraft

within a wake turbulence category and then calculating an average speed. And these speeds that are used are the manufacturer's designated “approach speed”. Figure 27 illustrates the various stages of arrival.

Figure 27: Various stages of arrival [26].

For each aircraft in the simulation a random number is generated and assigned as per the traffic mix (small, medium or heavy) probability table 3. This helps in assignment of a wake turbulence category. The process is then repeated to simulate the peak hour traffic flow.

The aircrafts in the simulation, depending on their type, are assigned runway occupancy time as derived from the AirTop simulations. Also, arrivals are simulated before departures as incoming aircrafts have priority over departing ones.

Once the Monte Carlo simulation has started and the cumulative time of events reaches 1 hour, the total number of aircrafts is counted. Since, the value of capacity is to be determined; the arrivals are given priority in the procedure followed here. The process is started at $t = 0$ minutes and the first arrival crosses the runway threshold at this point of time. The next aircraft has been assumed to be following the previous one at a

minimum separation. Hence, if the minimum required separation between the aircrafts is for example, 2.22 min, it means that the next aircraft is 2.22 min away from crossing runway threshold when the first one is at the threshold. The process continues until the simulation reaches 60 minutes. The count at the end of 1 hour gives arrival total for a runway.

The slots that are vacant are compared with simulation timings of the departing aircrafts on the runway. The scheduled departures are then allotted to the vacant slots of the runway. The procedure of slotting in departures is to find suitable gaps in the sequence of arriving traffic. It is to be taken care that a departure requires minimum separation time, which is greater than its own runway occupation time.

Thus outbound aircrafts on 20R have to wait for vacant slots between arrivals on 02L runway, while for departures vacant gaps on runway 02C are awaited by aircrafts departing from 20C. Also, the departures must not conflict with arrivals on 02C and 02L respectively.

This process is repeated for 60 minutes. The simulation is then stopped and the departures are counted. Any aircraft that has begun its take off or descent, but which has not left the runway within this 1 hour is not counted. The arrivals and departures are then added together to give an overall figure of theoretical maximum “peak hour” capacity.

In the scenarios where a runway is used for both arrivals and departures, it is possible to accommodate all the scheduled departures if all sufficient vacant clock times, irrespective of their duration are used. This means that possible delays or errors are not taken into account. The scenario is reasonable, given the fact that the concern is to calculate the maximum capacity.

The sum of the arriving and the departing aircrafts gives the total traffic on each runway, which is almost the same as the baseline capacity total.

An important point to be noted is that no departure is brought forward in time, thus resulting in very few vacant slots which are unutilized.

The other parameters that govern the estimation of runway capacity are:

1. The implementation ICAO procedures to govern and support high density runway operations at Changi.
2. The meteorological, weather conditions in Singapore.
3. The standard instrument departure route rules have been put into force to permit minimum time separation between departures.

The runway occupation times and separation times as per AirTOp analysis described in section 3.3.2 have been taken for the Monte Carlo calculations. Also, it is assumed that the aircrafts would roll slowly to the runway rather than stopping.

4. A big reservoir of aircrafts exists in the arrival - departure holding. Also, the taxiways and parking capacity is sufficient.

4.1 Results of Scenario 1: Full Mode Operations

As already described in this scenario runway 02C, which is near the residential areas is used only for arrivals and runway 20R is used solely for scheduled departures.

It is important to mention here that in this study the simulations for each scenario have been repeated 10 times so that steady state results are achieved before “peak hour” simulation. The results of “peak hour” simulations of aircrafts on 02C result in an average of 35 arrivals in the peak hour as depicted in table 16.

Aircraft type is S = Small, M = Medium, H = Heavy.

All the times namely: separation time (sep), runway occupancy time (ROT), enter runway time, exit runway time and runway unoccupied time are in minutes.

Random Number	Aircraft Type	Sep interval	ROT	EnterRunway	ExtRun	UnoccTime
0.99185811	M	0	0.67	0	0.67	1.11
0.486060894	M	1.78	0.67	1.78	2.45	1.11
0.881231506	M	1.78	0.67	3.56	4.23	1.11
0.485240242	M	1.78	0.67	5.34	6.01	1.11
0.861446373	M	1.78	0.67	7.12	7.79	0.44
0.160462879	H	1.11	0.83	8.23	9.06	0.95
0.288027756	H	1.78	0.83	10.01	10.84	0.95
0.272930256	H	1.78	0.83	11.79	12.62	0.95
0.013296678	H	1.78	0.83	13.57	14.4	0.95
0.035476486	H	1.78	0.83	15.35	16.18	0.95
0.403867266	H	1.78	0.83	17.13	17.96	1.39
0.737453609	M	2.22	0.67	19.35	20.02	0.44
0.089585213	H	1.11	0.83	20.46	21.29	3.13
0.006464978	S	3.96	0.5	24.42	24.92	0.61
0.074056244	H	1.11	0.83	25.53	26.36	0.95
0.08365003	H	1.78	0.83	27.31	28.14	0.95
0.258402526	H	1.78	0.83	29.09	29.92	1.39
0.966254026	M	2.22	0.67	31.31	31.98	1.11
0.59494624	M	1.78	0.67	33.09	33.76	0.44
0.120346083	H	1.11	0.83	34.2	35.03	0.95
0.389114361	H	1.78	0.83	35.98	36.81	1.39
0.625874645	M	2.22	0.67	38.2	38.87	0.44
0.034599357	H	1.11	0.83	39.31	40.14	1.39
0.823506661	M	2.22	0.67	41.53	42.2	1.11
0.686747147	M	1.78	0.67	43.31	43.98	0.44
0.365003098	H	1.11	0.83	44.42	45.25	0.95
0.230123702	H	1.78	0.83	46.2	47.03	0.95
0.275762882	H	1.78	0.83	47.98	48.81	1.39
0.773690259	M	2.22	0.67	50.2	50.87	1.11
0.45146209	M	1.78	0.67	51.98	52.65	0.44
0.181561427	H	1.11	0.83	53.09	53.92	1.39
0.666201199	M	2.22	0.67	55.31	55.98	0.44
0.200882661	H	1.11	0.83	56.42	57.25	0.95
0.060159193	H	1.78	0.83	58.2	59.03	1.39

Table 16: Arrival simulations on 02C

Similarly, for the departures on runway 20R, an average total of 30 outbound aircrafts is obtained as shown in table 17.

A total of 65 peak hour movements, arrivals and departures, are obtained.

Random Number	Aircraft Type	Sep interval	Run Occ	EnterRun	ExtRun	UnoccTime
0.959291015	M	0	0.67	0	0.67	1.11
0.937185845	M	1.78	0.67	1.78	2.45	0.44
0.053940986	H	1.11	0.83	2.89	3.72	2.28
0.933651806	M	3.11	0.67	6	6.67	1.11
0.782051734	M	1.78	0.67	7.78	8.45	1.11
0.725690404	M	1.78	0.67	9.56	10.23	0.44
0.311855026	H	1.11	0.83	10.67	11.5	1.84
0.020415809	H	2.67	0.83	13.34	14.17	2.28
0.779114046	M	3.11	0.67	16.45	17.12	0.44
0.139841783	H	1.11	0.83	17.56	18.39	2.28
0.641308773	M	3.11	0.67	20.67	21.34	1.11
0.591844878	M	1.78	0.67	22.45	23.12	1.11
0.663511155	M	1.78	0.67	24.23	24.9	0.44
0.361646644	H	1.11	0.83	25.34	26.17	1.84
0.420531128	H	2.67	0.83	28.01	28.84	2.28
0.702005153	M	3.11	0.67	31.12	31.79	1.11
0.529527755	M	1.78	0.67	32.9	33.57	0.44
0.137049817	H	1.11	0.83	34.01	34.84	2.28
0.859985203	M	3.11	0.67	37.12	37.79	1.11
0.796022973	M	1.78	0.67	38.9	39.57	1.11
0.499479427	M	1.78	0.83	40.68	41.51	0.28
0.314173444	H	1.11	0.83	41.79	42.62	1.84
0.42475402	H	2.67	0.83	44.46	45.29	2.28
0.993996046	M	3.11	0.67	47.57	48.24	0.44
0.026817941	H	1.11	0.83	48.68	49.51	2.28
0.586984395	M	3.11	0.67	51.79	52.46	0.44
0.120699699	H	1.11	0.67	52.9	53.57	2
0.269096268	H	2.67	0.67	55.57	56.24	2.44
0.912417449	M	3.11	0.83	58.68	59.51	0.28

Table 17: Departure simulations on 20R

4.2 Results of Scenario 2: Mix Mode Operations

In this case two arrival and departure, randomly mixed streams are considered for runways 02C, 02L and 20C, 20R respectively. Departures on 20C have to wait for vacant time slots on 02C by arrivals while departures on 20R only have to wait for vacant time slots on 02L.

Aircrafts that depart from 20C and 20R use the vacant clock times that remain after arrival of aircrafts on 02C and 02L respectively. The slots that are vacant are compared with simulation timings of the departing aircrafts on the runway. The scheduled departures are then allotted to the vacant slots of the runway. The procedure of slotting in departures is to find suitable gaps in the sequence of arriving traffic. It is to be taken care that a departure requires minimum separation time, which is greater than its own runway occupation time.

Also since the departures are to be slotted in the time gaps between arrivals, it is assumed that all the departures take maximum runway occupation time of 0.83 minutes or (53.6 seconds), as shown in table 15.

It is important to mention here that in this study the simulations for each scenario have been repeated 10 times so that steady state results are achieved before “peak hour” simulation. The results of “peak hour” simulations of Monte Carlo simulation in this case give an average capacity of 35 arrivals on 02C as shown in table 18 and 36 on 02L as shown in table 19, thus giving an average total of 71 movements for arrivals.

Random Number	Aircraft Type	Sep interval	Run Occ	EnterRun	ExtRun	UnoccTime
0.207713639	H	0	0.83	0	0.83	1.39
0.772783565	M	2.22	0.67	2.22	2.89	0.44
0.171037361	H	1.11	0.83	3.33	4.16	1.39
0.612863855	M	2.22	0.67	5.55	6.22	0.44
0.196779529	H	1.11	0.83	6.66	7.49	1.39
0.607249411	M	2.22	0.67	8.88	9.55	1.11
0.948478531	M	1.78	0.67	10.66	11.33	1.11
0.826218325	M	1.78	0.67	12.44	13.11	1.11
0.737654301	M	1.78	0.67	14.22	14.89	0.44
0.102156694	H	1.11	0.83	15.33	16.16	1.39
0.660092126	M	2.22	0.67	17.55	18.22	0.44
0.036783464	H	1.11	0.83	18.66	19.49	1.39
0.669743145	M	2.22	0.67	20.88	21.55	1.11
0.885982723	M	1.78	0.67	22.66	23.33	1.11
0.64118678	M	1.78	0.67	24.44	25.11	1.11
0.865581439	M	1.78	0.67	26.22	26.89	2.73
0.003580126	S	3.4	0.5	29.62	30.12	0.61
0.085591975	H	1.11	0.83	30.73	31.56	1.39
0.717248108	M	2.22	0.67	32.95	33.62	1.11
0.730892225	M	1.78	0.67	34.73	35.4	1.11
0.696537864	M	1.78	0.67	36.51	37.18	1.11
0.94648412	M	1.78	0.67	38.29	38.96	0.44
0.37105317	H	1.11	0.83	39.4	40.23	0.95
0.092207136	H	1.78	0.83	41.18	42.01	0.95
0.219994919	H	1.78	0.83	42.96	43.79	1.39
0.853846571	M	2.22	0.67	45.18	45.85	0.44
0.200922196	H	1.11	0.83	46.29	47.12	0.95
0.378795022	H	1.78	0.83	48.07	48.9	0.95
0.33629532	H	1.78	0.83	49.85	50.68	1.39
0.730607327	M	2.22	0.67	52.07	52.74	0.44
0.167627231	H	1.11	0.83	53.18	54.01	1.39
0.544769471	M	2.22	0.67	55.4	56.07	1.11
0.991242507	M	1.78	0.67	57.18	57.85	1.11
0.55764866	M	1.78	0.67	58.96	59.63	1.11

Table 18: Arrival simulations on 02C

Random Number	Aircraft Type	Sep interval	Run Occ	EnterRun	ExtRun	UnoccTime
0.769268475	M	0	0.67	0	0.67	1.11
0.864184773	M	1.78	0.67	1.78	2.45	0.44
0.315160526	H	1.11	0.83	2.89	3.72	0.95
0.201140678	H	1.78	0.83	4.67	5.5	3.13
0.002715113	S	3.96	0.5	8.63	9.13	0.61
0.662735565	M	1.11	0.67	9.74	10.41	1.11
0.698110028	M	1.78	0.67	11.52	12.19	0.44
0.17340978	H	1.11	0.83	12.63	13.46	1.39
0.884105333	M	2.22	0.67	14.85	15.52	1.11
0.98817032	M	1.78	0.67	16.63	17.3	1.11
0.445156229	M	1.78	0.67	18.41	19.08	0.44
0.134530594	H	1.11	0.83	19.52	20.35	1.39
0.476206185	M	2.22	0.67	21.74	22.41	1.11
0.63203095	M	1.78	0.67	23.52	24.19	0.44
0.358718709	H	1.11	0.83	24.63	25.46	1.39
0.595984233	M	2.22	0.67	26.85	27.52	0.44
0.206764445	H	1.11	0.83	27.96	28.79	0.95
0.025671958	H	1.78	0.83	29.74	30.57	1.39
0.794436892	M	2.22	0.67	31.96	32.63	1.11
0.582616068	M	1.78	0.67	33.74	34.41	1.11
0.680334463	M	1.78	0.67	35.52	36.19	1.11
0.588041821	M	1.78	0.67	37.3	37.97	0.44
0.380987755	H	1.11	0.83	38.41	39.24	1.39
0.790493013	M	2.22	0.67	40.63	41.3	0.44
0.315202653	H	1.11	0.83	41.74	42.57	1.39
0.816151757	M	2.22	0.67	43.96	44.63	1.11
0.779692959	M	1.78	0.67	45.74	46.41	0.44
0.271924957	H	1.11	0.83	46.85	47.68	1.39
0.590076011	M	2.22	0.67	49.07	49.74	0.44
0.207132925	H	1.11	0.83	50.18	51.01	1.39
0.693965854	M	2.22	0.67	52.4	53.07	1.11
0.994345544	M	1.78	0.67	54.18	54.85	0.44
0.198176276	H	1.11	0.83	55.29	56.12	0.95
0.373895602	H	1.78	0.83	57.07	57.9	1.39
0.474387763	M	2.22	0.67	59.29	59.96	1.11

Table 19: Arrival simulations on 02L

Aircrafts that depart from 20C and 20R use the vacant clock times that remain after arrival of aircrafts on 02C and 02L respectively. The slots that are vacant are compared with simulation timings of the departing aircrafts on the runway. The scheduled departures are then allotted to the vacant slots of the runway. The procedure of slotting in departures is to find suitable gaps in the sequence of arriving traffic. It is to be taken care that a departure requires minimum separation time, which is greater than its own runway occupation time.

Average departure movements on 20C total up to 30. Whilst those on 20R give a total of 31. During allocation of the departures in the runway unoccupied time slots, since it is to be found that how many total movements can be possible in 1 hour, it is found that on runway 20C a total of 18 departures out of 30 can be allotted time gaps in the 1 hour simulation interval. This can be seen in table 20.

Random Number	Aircraft Type	Sep interval	Run Occ	EnterRun	ExtRun
0.595733021	M	0	0.83	0.83	1.66
0.680101178	M	1.78	0.83	4.16	4.99
0.666779778	M	1.78	0.83	11.33	12.16
0.12255214	H	1.11	0.83	13.27	14.1
0.409284732	H	2.67	0.83	16.77	17.6
0.136846014	H	2.67	0.83	20.27	21.1
0.742980936	M	1.78	0.83	24.21	25.04
0.461394746	M	1.78	0.83	26.82	27.65
0.899711467	M	1.78	0.83	29.43	30.26
0.872456041	M	3.11	0.83	33.62	34.45
0.894557125	M	1.78	0.83	36.23	37.06
0.035660505	H	1.11	0.83	38.96	39.79
0.051513451	H	2.67	0.83	42.46	43.29
0.055351776	H	2.67	0.83	45.96	46.79
0.048976913	H	1.11	0.83	47.12	47.95
0.940023381	M	3.11	0.83	51.06	51.89
0.179258397	H	1.11	0.83	53	53.83
0.401186126	H	2.67	0.83	56.5	57.33

Table 20: Departure simulations on 20C

While in case of runway 20R a total of 18 out of 31 can be allotted to the slot gaps in the 1 hour period. Table 21 depicts the allotted departures on runway 20R.

Random Number	Aircraft Type	Sep interval	Run Occ	EnterRun	ExtRun
0.348056684	H	0	0.83	0.67	1.5
0.727561161	M	1.78	0.83	3.72	4.55
0.829015909	M	3.11	0.83	7.66	8.49
0.551649503	M	1.78	0.83	12.19	13.02
0.79593965	M	1.78	0.83	14.8	15.63
0.539642096	M	1.78	0.83	17.41	18.24
0.024981425	H	1.11	0.83	19.35	20.18
0.852385769	M	3.11	0.83	23.29	24.12
0.064229824	H	1.11	0.83	27.52	28.35
0.398781699	H	2.67	0.83	31.02	31.85
0.9556334	M	3.11	0.83	34.96	35.79
0.125413171	H	1.11	0.83	36.9	37.73
0.099552621	H	2.67	0.83	40.4	41.23
0.937495757	M	1.78	0.83	43.01	43.84
0.009134678	S	4.53	0.83	48.37	49.2
0.503657741	M	3.11	0.83	52.31	53.14
0.535602776	M	1.78	0.83	56.12	56.95
0.43745324	M	1.78	0.83	58.73	59.56

Table 21: Departure simulations on 20R

This gives average total number of departures as 36 and the average total movements (arrivals + departures) as 107. On the other hand if departure gaps required more than one minute, then the total of departures would further reduce.

4.3 Results of Scenario 3: Managed Departure Operations

In this case, randomly mixed arrival streams were considered for runways 02C and 02L while the departures are managed on the runways. On the other hand, departures were “managed”. “Managed” departure operations means that only medium weight aircrafts take off from 20C, with heavy and small aircrafts departing from runway 20R. Now in this final case the departures are slotted in between arrivals by aircraft type.

The slots that are vacant are compared with simulation timings of the departing aircrafts on the runway. The scheduled departures are then allotted to the vacant slots of the runway. The procedure of slotting in departures is to find suitable gaps in the sequence of arriving traffic. It is to be taken care that a departure requires minimum separation time, which is greater than its own runway occupation time. Thus heavy and small outbound aircrafts on 20R have to wait for vacant slots between arrivals on 02L runway, while for departures vacant gaps on runway 02C are awaited by “medium aircrafts” departing from 20C. Also, the departures must not conflict with arrivals on 02C and 02L respectively.

It is important to mention here that in this study the simulations for each scenario have been repeated 10 times so that steady state results are achieved before “peak hour” simulation. The results of “peak hour” simulations of Monte Carlo simulation in this case give an arrival total of 34 on 02C, as shown in table 22, and 35 on 02L as shown in table 23, thus a total of 69 is achieved. Also, since the departures are to be slotted in the time gaps between arrivals, it is assumed that all the departures take maximum runway occupation time of 0.83 minutes or (53.6 seconds), as shown in table 15.

Departures on the other hand, average a total of 28 medium type aircrafts on 20C, as shown in table 24. On 20R, heavy and small departures give a count of 16 as shown in table 25. The number of medium aircrafts that have been slotted on runway 20C are greater because of the separation time interval being always constant. Because of “managed” departures, according to which only medium aircrafts depart from runway 20C. This totals to 44 departures and average total (arrival + departure) movements as 113.

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.977149752	M	0	0.67	0	0.67
0.60166528	M	1.78	0.67	1.78	2.45
0.561342322	M	1.78	0.67	3.56	4.23
0.855434558	M	1.78	0.67	5.34	6.01
0.871389545	M	1.78	0.67	7.12	7.79
0.0924208	H	1.11	0.83	8.23	9.06
0.422747792	H	1.78	0.83	10.01	10.84
0.947084852	M	2.22	0.67	12.23	12.9
0.712552328	M	1.78	0.67	14.01	14.68
0.431978521	M	1.78	0.67	15.79	16.46
0.55823596	M	1.78	0.67	17.57	18.24
0.006194572	S	3.4	0.5	20.97	21.47
0.345176435	H	1.11	0.83	22.08	22.91
0.346665293	H	1.78	0.83	23.86	24.69
0.25114025	H	1.78	0.83	25.64	26.47
0.838543076	M	2.22	0.67	27.86	28.53
0.049824646	H	1.11	0.83	28.97	29.8
0.181826104	H	1.78	0.83	30.75	31.58
0.320507591	H	1.78	0.83	32.53	33.36
0.33986728	H	1.78	0.83	34.31	35.14
0.154936236	H	1.78	0.83	36.09	36.92
0.971369716	M	2.22	0.67	38.31	38.98
0.91875789	M	1.78	0.67	40.09	40.76
0.739366327	M	1.78	0.67	41.87	42.54
0.292237309	H	1.11	0.83	42.98	43.81
0.889483342	M	2.22	0.67	45.2	45.87
0.752042406	M	1.78	0.67	46.98	47.65
0.58493771	M	1.78	0.67	48.76	49.43
0.484449881	M	1.78	0.67	50.54	51.21
0.398645203	H	1.11	0.83	51.65	52.48
0.917278259	M	2.22	0.67	53.87	54.54
0.958682896	M	1.78	0.67	55.65	56.32
0.322762735	H	1.11	0.83	56.76	57.59
0.114959185	H	1.78	0.83	58.54	59.37

Table 22: Arrival simulations on 02C

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.507028356	M	0	0.67	0	0.67
0.666542199	M	1.78	0.67	1.78	2.45
0.70774666	M	1.78	0.67	3.56	4.23
0.824380225	M	1.78	0.67	5.34	6.01
0.136610901	H	1.11	0.83	6.45	7.28
0.364312846	H	1.78	0.83	8.23	9.06
0.23023392	H	1.78	0.83	10.01	10.84
0.987185783	M	2.22	0.67	12.23	12.9
0.887769847	M	1.78	0.67	14.01	14.68
0.788912499	M	1.78	0.67	15.79	16.46
0.708553365	M	1.78	0.67	17.57	18.24
0.601159955	M	1.78	0.67	19.35	20.02
0.501847365	M	1.78	0.67	21.13	21.8
0.767007313	M	1.78	0.67	22.91	23.58
0.116915989	H	1.11	0.83	24.02	24.85
0.627201765	M	2.22	0.67	26.24	26.91
0.833559401	M	1.78	0.67	28.02	28.69
0.077031758	H	1.11	0.83	29.13	29.96
0.560672347	M	2.22	0.67	31.35	32.02
0.351671581	H	1.11	0.83	32.46	33.29
0.228467946	H	1.78	0.83	34.24	35.07
0.612897147	M	2.22	0.67	36.46	37.13
0.529224203	M	1.78	0.67	38.24	38.91
0.083278309	H	1.11	0.83	39.35	40.18
0.317787442	H	1.78	0.83	41.13	41.96
0.29295607	H	1.78	0.83	42.91	43.74
0.760271255	M	2.22	0.67	45.13	45.8
0.791661	M	1.78	0.67	46.91	47.58
0.126744372	H	1.11	0.83	48.02	48.85
0.374219324	H	1.78	0.83	49.8	50.63
0.38198309	H	1.78	0.83	51.58	52.41
0.389748881	H	1.78	0.83	53.36	54.19
0.113233865	H	1.78	0.83	55.14	55.97
0.404513939	H	1.78	0.83	56.92	57.75
0.086674514	H	1.78	0.83	58.7	59.53

Table 23: Arrival simulations on 02L

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.824121887	M	0	0.83	0.67	1.5
0.548242114	M	1.78	0.83	2.45	3.28
0.649030742	M	1.78	0.83	4.23	5.06
0.879057668	M	1.78	0.83	6.01	6.84
0.851816716	M	1.78	0.83	9.06	9.89
0.449467839	M	1.78	0.83	10.84	11.67
0.864340298	M	1.78	0.83	12.9	13.73
0.960852045	M	1.78	0.83	14.68	15.51
0.79473957	M	1.78	0.83	16.46	17.29
0.461311281	M	1.78	0.83	18.24	19.07
0.722805378	M	1.78	0.83	22.91	23.74
0.502587358	M	1.78	0.83	24.69	25.52
0.554505087	M	1.78	0.83	26.47	27.3
0.485463341	M	1.78	0.83	29.8	30.63
0.502750505	M	1.78	0.83	31.58	32.41
0.853642294	M	1.78	0.83	33.36	34.19
0.671893158	M	1.78	0.83	35.14	35.97
0.983301038	M	1.78	0.83	36.92	37.75
0.495718294	M	1.78	0.83	38.98	39.81
0.508315236	M	1.78	0.83	40.76	41.59
0.578183902	M	1.78	0.83	43.81	44.64
0.707670983	M	1.78	0.83	45.87	46.7
0.565688684	M	1.78	0.83	47.65	48.48
0.995790907	M	1.78	0.83	49.43	50.26
0.804443479	M	1.78	0.83	52.48	53.31
0.440785932	M	1.78	0.83	54.54	55.37
0.589485681	M	1.78	0.83	57.59	58.42
0.684275111	M	1.78	0.83	59.37	60.2

Table 24: Departure simulations on 20C

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.049943423	H	0	0.83	0.67	1.5
0.197554465	H	2.67	0.83	4.23	5.06
0.357369935	H	2.67	0.83	10.84	11.67
0.392701354	H	2.67	0.83	14.68	15.51
0.304100494	H	2.67	0.83	18.24	19.07
0.201148274	H	2.67	0.83	21.8	22.63
0.156793521	H	2.67	0.83	24.85	25.68
0.189856168	H	2.67	0.83	29.96	30.79
0.187630221	H	2.67	0.83	33.29	34.12
0.156038893	H	2.67	0.83	37.13	37.96
0.164063821	H	2.67	0.83	41.96	42.79
0.002525581	S	4.53	0.83	48.85	49.68
0.390255115	H	1.26	0.83	52.41	53.24
0.422814423	H	2.67	0.83	55.97	56.8
0.126327649	H	2.67	0.83	57.75	58.58
0.38811741	H	2.67	0.83	59.53	60.36

Table 25: Departure simulations on 20R

4.4 Changi 3rd new runway scenario

An option being considered for increasing Changi's runway capacity is that of construction of a 3rd runway. As per CAAS and the airport commission, the runway would be built far enough so that all runways can operate simultaneously [34] [39].

In simulation of this scenario, it has been assumed that the new proposed terminal shall be used by all aircrafts that use the new runway thus avoiding the need of crossing existing runways. Also, a traffic mix similar to that of runway 1 and runway 2 would be handled by the new runway.

Table 26 shows the simulations for current runways and also for the 3rd runway. The new total peak hour capacity is about 160 movements.

Simulation	02C arrivals	20C departures	02L arrivals	20R departures	3rd Runway arrivals	3rd Runway departures	Total
1	33	20	32	20	44	11	160
2	34	19	42	12	41	14	162
3	36	16	36	14	40	14	156
4	37	15	37	15	42	13	159
5	35	16	34	16	41	13	155
6	35	16	36	16	41	15	159
7	36	14	37	16	37	19	159
8	34	19	36	17	45	9	160
9	38	18	33	20	44	11	164
10	32	24	37	15	43	11	162
Average	35	18	36	16	42	13	160

Table 26: Total Capacity after building 3rd runway.

Table 27 shows a comparison between current situation capacity at Changi and the scenario when 3rd runway will be ready and be operational. It can clearly be seen that an increase of 41.6% will be there in runway capacity when the third runway is operational by 2020 [34].

	Current situation capacity	Changi 3rd runway capacity	Difference	Percentage change
Changi	113	160	47	41.60%

Table 27: Comparison of Changi's 3rd Runway and Current result of simulation.

Chapter 5: Conclusions and Discussion

Table 28 summarizes the capacity estimates calculated in the Monte Carlo analysis. It is important to mention here once again that in this study the simulations for each scenario have been repeated 10 times so that steady state results are achieved before “peak hour” simulation. The tables 16 to 28 depict the results of “peak hour” simulations.

It is to be noted that the estimates are for a peak period of 1 hour. Therefore, the number of arrivals and departures may not be equal. In table 28 the number of arrivals exceeds the number of departures. To explain this, in table 28 arrivals on runway 02C under “Mixed mode” are 35, whereas the corresponding departures on runway 20C are only 18. This does not mean that airport will be overcrowded with arrivals. As already mentioned, the assumption is that arrivals get priority over departures and the estimates are for a peak period of 1 hour.

	Scenarios		
	1 (Full Mode)	2 (Mixed Mode)	3(Managed Dep. Ops)
Arrivals 02C	35	35	34
Arrivals 02L	-	36	35
Departures 20C	-	18	28
Departures 20R	30	18	16
Total	65	107	113

Table 28: Runway capacity: Scenarios 1 to 3

It is evident from table 28 that in scenario 1 the total number of movements is much less compared to other two cases.

In the third case (scenario 3), where there is segregation by aircraft type the runways capacity is more than the first two cases. Thus maximum utilization of the runways could be realized in this case.

As per the Changi airport website [39], the total traffic movements in the year 2013 were 343,765 at Changi. Following a study, CAAS concluded that the existing two runways can handle traffic movements up to 430,000 annually, which is about 25% more than the traffic movements recorded in the year 2013 [39].

The maximum peak hour capacity at Changi, based on the study by CAAS [39], can be roughly estimated to be 82 movements, which is 25% greater than the current peak hour figure of 64 movements.

Table 29 shows a comparison between the current declared capacity of Changi Airport and the results of Monte Carlo analysis. It can be observed that in scenario 3, the value of runway capacity is 27% more than the current value of declared capacity at Changi.

Scenario	Current situation capacity	Monte Carlo Results	Difference	Percentage change
1	82	65	-17	-20.70%
2	82	107	25	24.30%
3	82	113	31	27%

Table 29: Comparison between Monte Carlo Results and Capacity of Changi.

Figure 28 shows a rough estimate of traffic movements at Changi compared to world's other busy airports. In 2014 Changi was the 6th busiest airport in the world. Also, the passenger traffic rose by 2% compared to that in 2013.

Flying high

Top 10 world airport traffic in 2013 and 2014

Figure 28: Traffic movements at Changi compared to world's other busy airports [33]

Through the use of AirTOP simulator and Monte Carlo simulation this study has examined runway occupancy time, separation time between aircrafts and the different capacity scenarios respectively at Changi airport. The results approximately translate to a 27% increase in total “peak hour” movements. Although, it does not take into account some realistic factors of absolute capacity but the analysis provides comparable figures for potential capacity at the airport. Also, the capacity figures produced through this research provide a platform based on which the relative benefits of expansion projects at Changi may be examined in greater detail.

This study has defined a concept of estimating runway occupancy time, separation time and maximum capacity. While the study provides comparable figures for future capacity, it does not advocate any particular development as it is based on simulations of relative capacity at the peak hour. One assumption of this study is that, while performing the Monte Carlo simulations to estimate the capacity of Changi, every simulation starts with an empty airport, which might not be the case in “peak hour”. Therefore, to take this into account and get more realistic estimates of absolute capacity, a queuing model is proposed for future research.

For future work, it would be beneficial to use a queuing model to get more realistic runway capacity estimates of reduced separation concepts. Furthermore, including weather data in the study could capture the effect of strong head wind on inter-arrival separations, and the effect of rain and storms on runway occupancy times.

Blumstein developed a probabilistic queuing model to estimate capacity when a runway is used solely for arrivals [1]. This model may be extended to include departures and mixed movements also.

The capacity queuing model assumes that arriving aircraft share a common final approach path with a known final approach fix. The length of the final approach is denoted by r . The leading aircraft type (small, medium or heavy) is denoted with the letter i , and the following aircraft type with the letter j . The inter-arrival minimum

separation requirements are maintained at all times on approach. S_{ij} indicates the minimum required separation between the leading aircraft type and the following aircraft type. Similarly, T_{ij} is the minimum time interval between successive arrivals for the aircraft i and j . The final approach velocities are denoted by v_i and v_j , respectively.

The minimum time interval between successive arrivals is dependent on whether the lead aircraft or trailing aircraft is flying the final approach faster. When the leading aircraft is flying faster, the separation between the pair is at its minimum when the leading aircraft begins the final approach at the final approach fix.

The minimum time separation then can be calculated from equation 1.

$$T_{ij} = \max\left[\frac{r+s_{ij}}{v_j} - \frac{r}{v_i}, ROT_i\right], \text{ when } v_i > v_j \quad (1)$$

In the closing case, the trailing aircraft is faster than the leading aircraft and the minimum separation between them occurs when the leading aircraft crosses the runway threshold. The minimum time interval for the closing case can be calculated as illustrated in Equation 2.

$$T_{ij} = \max\left[\frac{s_{ij}}{v_j}, ROT_i\right], \text{ when } v_i \leq v_j \quad (2)$$

In both the opening and closing case, however, the minimum time interval between successive arrivals is also influenced by the runway occupancy time of the leading aircraft. Since simultaneous runway occupancy is not allowed, the leading aircraft needs to exit the runway before the trailing aircraft is allowed to land. The queuing model accounts for this requirement by evaluating both the minimum separation and the runway occupancy, and takes the larger of the two as the minimum landing time interval.

The probability of a given pair of aircraft weight categories can be evaluated based on a given traffic mix. The expected time an aircraft pair takes to land can be calculated from equation 3, where b indicates a buffer time added to the system. The buffer is an increased safety margin.

$$E(t) = \sum P_{ij} (T_{ij} + b) \quad (3)$$

Once the expected time between consecutive landings has been calculated, the capacity of the runway is the inverse of the expected time as presented in equation 4.

$$\mu = \frac{1}{E(t)} \quad (4)$$

Lastly, coming back to Monte Carlo analysis in this study, it is to be noted that the Monte Carlo analysis takes into account the “peak hour” of 7 days of operations of September 2014. The values of total “peak hour” movements or the “peak hour” itself may vary according to the normal or festive seasons of an year.

However, even after considering all the assumptions and above mentioned limitations, the results found in this study provide a comparable base that might allow to identify crucial parameters and postponement of huge infrastructure investment at Changi while still meeting the rising air transport demand for another 2 - 4 years. Indeed, the result reported here might also help in the declared capacity at Changi airport being increased from the current figure of 82.

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Appendix

10 “Warm up” samples of Monte Carlo simulation for arrivals on 02C

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.81211698	M	0	0.67	0	0.67
0.412414159	H	1.11	0.83	1.11	1.94
0.205987614	H	1.78	0.83	2.89	3.72
0.158770346	H	1.78	0.83	4.67	5.5
0.884305036	M	2.22	0.67	6.89	7.56
0.116737282	H	1.11	0.83	8	8.83
0.234045864	H	1.78	0.83	9.78	10.61
0.810696283	M	2.22	0.67	12	12.67
0.77502094	M	1.78	0.67	13.78	14.45

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.894561001	M	0	0.67	0	0.67
0.235173384	H	1.11	0.83	1.11	1.94
0.859115104	M	2.22	0.67	3.33	4
0.711231093	M	1.78	0.67	5.11	5.78
0.731074734	M	1.78	0.67	6.89	7.56
0.098739651	H	1.11	0.83	8	8.83
0.438437724	M	2.22	0.67	10.22	10.89
0.018760379	H	1.11	0.83	11.33	12.16
0.06686887	H	1.78	0.83	13.11	13.94
0.533233046	M	2.22	0.67	15.33	16

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.512163294	M	0	0.67	0	0.67
0.566342099	M	1.78	0.67	1.78	2.45
0.512638644	M	1.78	0.67	3.56	4.23
0.763088596	M	1.78	0.67	5.34	6.01
0.815294015	M	1.78	0.67	7.12	7.79
0.190920545	H	1.11	0.83	8.23	9.06
0.898148862	M	2.22	0.67	10.45	11.12
0.855917905	M	1.78	0.67	12.23	12.9
0.707091172	M	1.78	0.67	14.01	14.68
0.193088614	H	1.11	0.83	15.12	15.95

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.940778765	M	0	0.67	0	0.67
0.21765556	H	1.11	0.83	1.11	1.94
0.253715502	H	1.78	0.83	2.89	3.72
0.000950942	S	3.96	0.5	6.85	7.35
0.219651863	H	1.11	0.83	7.96	8.79
0.568026769	M	2.22	0.67	10.18	10.85
0.680453842	M	1.78	0.67	11.96	12.63
0.544467686	M	1.78	0.67	13.74	14.41
0.457257536	M	1.78	0.67	15.52	16.19
0.472476861	M	1.78	0.67	17.3	17.97

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.098439019	H	0	0.83	0	0.83
0.172451757	H	1.78	0.83	1.78	2.61
0.342141093	H	1.78	0.83	3.56	4.39
0.352818019	H	1.78	0.83	5.34	6.17
0.455460093	M	2.22	0.67	7.56	8.23
0.77302165	M	1.78	0.67	9.34	10.01
0.330482458	H	1.11	0.83	10.45	11.28
0.873842637	M	2.22	0.67	12.67	13.34
0.748953593	M	1.78	0.67	14.45	15.12
0.000239771	S	3.4	0.5	17.85	18.35

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.008164607	S	0	0.5	0	0.5
0.605017169	M	1.11	0.67	1.11	1.78
0.340626046	H	1.11	0.83	2.22	3.05
0.261906157	H	1.78	0.83	4	4.83
0.541846234	M	2.22	0.67	6.22	6.89
0.61290209	M	1.78	0.67	8	8.67
0.223736424	H	1.11	0.83	9.11	9.94
0.878755179	M	2.22	0.67	11.33	12
0.186403316	H	1.11	0.83	12.44	13.27

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.682874101	M	0	0.67	0	0.67
0.416948491	H	1.11	0.83	1.11	1.94
0.801352466	M	2.22	0.67	3.33	4
0.716976216	M	1.78	0.67	5.11	5.78
0.44425869	M	1.78	0.67	6.89	7.56
0.771454143	M	1.78	0.67	8.67	9.34
0.961905226	M	1.78	0.67	10.45	11.12
0.904162599	M	1.78	0.67	12.23	12.9
0.268182328	H	1.11	0.83	13.34	14.17
0.453127881	M	2.22	0.67	15.56	16.23

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.584724868	M	0	0.67	0	0.67
0.739036765	M	1.78	0.67	1.78	2.45
0.992470606	M	1.78	0.67	3.56	4.23
0.906413973	M	1.78	0.67	5.34	6.01
0.058221698	H	1.11	0.83	6.45	7.28
0.39320331	H	1.78	0.83	8.23	9.06
0.754370137	M	2.22	0.67	10.45	11.12
0.922876242	M	1.78	0.67	12.23	12.9
0.709924673	M	1.78	0.67	14.01	14.68
0.038095465	H	1.11	0.83	15.12	15.95

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.353079738	H	0	0.83	0	0.83
0.391050676	H	1.78	0.83	1.78	2.61
0.562732628	M	2.22	0.67	4	4.67
0.315770311	H	1.11	0.83	5.11	5.94
0.447738984	M	2.22	0.67	7.33	8
0.731729739	M	1.78	0.67	9.11	9.78
0.488731274	M	1.78	0.67	10.89	11.56
0.255168105	H	1.11	0.83	12	12.83
0.974823152	M	2.22	0.67	14.22	14.89
0.016114555	H	1.11	0.83	15.33	16.16

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.138736576	H	0	0.83	0	0.83
0.095923045	H	1.78	0.83	1.78	2.61
0.487840792	M	2.22	0.67	4	4.67
0.183164964	H	1.11	0.83	5.11	5.94
0.648402011	M	2.22	0.67	7.33	8
0.470589435	M	1.78	0.67	9.11	9.78
0.330883929	H	1.11	0.83	10.22	11.05
0.039152833	H	1.78	0.83	12	12.83
0.559021261	M	2.22	0.67	14.22	14.89
0.552525315	M	1.78	0.67	16	16.67

10 “Warm up” samples of Monte Carlo simulation for departures on 20C

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.561120161	M	0	0.83	0	0.83
0.029125331	H	1.11	0.83	1.11	1.94
0.119403355	H	2.67	0.83	3.78	4.61
0.533236791	M	1.11	0.83	4.89	5.72
0.735734415	M	1.78	0.83	6.67	7.5
0.612873223	M	1.78	0.83	8.45	9.28
0.726959435	M	1.78	0.83	10.23	11.06
0.351782403	H	1.11	0.83	11.34	12.17
0.283999621	H	2.67	0.83	14.01	14.84

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.445682597	M	0	0.83	0	0.83
0.655729592	M	1.78	0.83	1.78	2.61
0.127305011	H	1.11	0.83	2.89	3.72
0.78161631	M	3.11	0.83	6	6.83
0.671810619	M	1.78	0.83	7.78	8.61
0.880351331	M	1.78	0.83	9.56	10.39
0.916904901	M	1.78	0.83	11.34	12.17
0.93560594	M	1.78	0.83	13.12	13.95
0.668052741	M	1.78	0.83	14.9	15.73
0.558883788	M	1.78	0.83	16.68	17.51

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.220486954	H	0	0.83	0	0.83
0.958264516	M	3.11	0.83	3.11	3.94
0.879193057	M	1.78	0.83	4.89	5.72
0.199165318	H	1.11	0.83	6	6.83
0.519835959	M	3.11	0.83	9.11	9.94
0.744715555	M	1.78	0.83	10.89	11.72
0.450625618	M	1.78	0.83	12.67	13.5
0.019797152	H	1.11	0.83	13.78	14.61
0.64996979	M	3.11	0.83	16.89	17.72
0.320827932	H	1.11	0.83	18	18.83

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.832780386	M	0	0.83	0	0.83
0.556400744	M	1.78	0.83	1.78	2.61
0.074152536	H	1.11	0.83	2.89	3.72
0.864752027	M	3.11	0.83	6	6.83
0.48746199	M	1.78	0.83	7.78	8.61
0.571346076	M	1.78	0.83	9.56	10.39
0.689864279	M	1.78	0.83	11.34	12.17
0.991319172	M	1.78	0.83	13.12	13.95
0.697213334	M	1.78	0.83	14.9	15.73
0.03612964	H	1.11	0.83	16.01	16.84

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.182496454	H	0	0.83	0	0.83
0.045524055	H	2.67	0.83	2.67	3.5
0.950830969	M	3.11	0.83	5.78	6.61
0.014396212	H	1.11	0.83	6.89	7.72
0.058253231	H	2.67	0.83	9.56	10.39
0.232763151	H	2.67	0.83	12.23	13.06
0.202799369	H	2.67	0.83	14.9	15.73
0.30908261	H	2.67	0.83	17.57	18.4
0.168976907	H	2.67	0.83	20.24	21.07
0.498324103	M	3.11	0.83	23.35	24.18

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.537874559	M	0	0.83	0	0.83
0.571736011	M	1.78	0.83	1.78	2.61
0.227044858	H	1.11	0.83	2.89	3.72
0.734461738	M	3.11	0.83	6	6.83
0.099545138	H	1.11	0.83	7.11	7.94
0.824916278	M	3.11	0.83	10.22	11.05
0.587120533	M	1.78	0.83	12	12.83
0.356340751	H	1.11	0.83	13.11	13.94
0.134614918	H	2.67	0.83	15.78	16.61

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.056750129	H	0	0.83	0	0.83
0.384256441	H	2.67	0.83	2.67	3.5
0.1153289	H	2.67	0.83	5.34	6.17
0.367743807	H	2.67	0.83	8.01	8.84
0.488666635	M	3.11	0.83	11.12	11.95
0.469707246	M	1.78	0.83	12.9	13.73
0.568133363	M	1.78	0.83	14.68	15.51
0.722522995	M	1.78	0.83	16.46	17.29
0.748114801	M	1.78	0.83	18.24	19.07
0.012622557	H	1.11	0.83	19.35	20.18

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.005571391	S	0	0.83	0	0.83
0.487432094	M	1.26	0.83	1.26	2.09
0.698905237	M	1.78	0.83	3.04	3.87
0.628305364	M	1.78	0.83	4.82	5.65
0.030494596	H	1.11	0.83	5.93	6.76
0.242254787	H	2.67	0.83	8.6	9.43
0.979311218	M	3.11	0.83	11.71	12.54
0.292342715	H	1.11	0.83	12.82	13.65
0.638885638	M	3.11	0.83	15.93	16.76
0.726208355	M	1.78	0.83	17.71	18.54

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.339174038	H	0	0.83	0	0.83
0.347290751	H	2.67	0.83	2.67	3.5
0.614819375	M	3.11	0.83	5.78	6.61
0.362148804	H	1.11	0.83	6.89	7.72
0.145393866	H	2.67	0.83	9.56	10.39
0.218185214	H	2.67	0.83	12.23	13.06
0.098569268	H	2.67	0.83	14.9	15.73
0.238049342	H	2.67	0.83	17.57	18.4
0.72633102	M	3.11	0.83	20.68	21.51
0.913500413	M	1.78	0.83	22.46	23.29

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.498211706	M	0	0.83	0	0.83
0.202946895	H	1.11	0.83	1.11	1.94
0.27787862	H	2.67	0.83	3.78	4.61
0.826893936	M	3.11	0.83	6.89	7.72
0.055670653	H	1.11	0.83	8	8.83
0.438682753	M	3.11	0.83	11.11	11.94
0.659300468	M	1.78	0.83	12.89	13.72
0.420495938	H	1.11	0.83	14	14.83
0.889373799	M	3.11	0.83	17.11	17.94
0.840009116	M	1.78	0.83	18.89	19.72

10 “Warm up” samples of Monte Carlo simulation for arrivals on 02L

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.507028356	M	0	0.67	0	0.67
0.666542199	M	1.78	0.67	1.78	2.45
0.70774666	M	1.78	0.67	3.56	4.23
0.824380225	M	1.78	0.67	5.34	6.01
0.136610901	H	1.11	0.83	6.45	7.28
0.364312846	H	1.78	0.83	8.23	9.06
0.23023392	H	1.78	0.83	10.01	10.84
0.987185783	M	2.22	0.67	12.23	12.9
0.887769847	M	1.78	0.67	14.01	14.68
0.788912499	M	1.78	0.67	15.79	16.46

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.353079738	H	0	0.83	0	0.83
0.391050676	H	1.78	0.83	1.78	2.61
0.562732628	M	2.22	0.67	4	4.67
0.315770311	H	1.11	0.83	5.11	5.94
0.447738984	M	2.22	0.67	7.33	8
0.731729739	M	1.78	0.67	9.11	9.78
0.488731274	M	1.78	0.67	10.89	11.56
0.255168105	H	1.11	0.83	12	12.83
0.974823152	M	2.22	0.67	14.22	14.89
0.016114555	H	1.11	0.83	15.33	16.16

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.81211698	M	0	0.67	0	0.67
0.412414159	H	1.11	0.83	1.11	1.94
0.205987614	H	1.78	0.83	2.89	3.72
0.158770346	H	1.78	0.83	4.67	5.5
0.884305036	M	2.22	0.67	6.89	7.56
0.116737282	H	1.11	0.83	8	8.83
0.234045864	H	1.78	0.83	9.78	10.61
0.810696283	M	2.22	0.67	12	12.67
0.77502094	M	1.78	0.67	13.78	14.45

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.682874101	M	0	0.67	0	0.67
0.416948491	H	1.11	0.83	1.11	1.94
0.801352466	M	2.22	0.67	3.33	4
0.716976216	M	1.78	0.67	5.11	5.78
0.44425869	M	1.78	0.67	6.89	7.56
0.771454143	M	1.78	0.67	8.67	9.34
0.961905226	M	1.78	0.67	10.45	11.12
0.904162599	M	1.78	0.67	12.23	12.9
0.268182328	H	1.11	0.83	13.34	14.17
0.453127881	M	2.22	0.67	15.56	16.23

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.608860862	M	0	0.67	0	0.67
0.846108929	M	1.78	0.67	1.78	2.45
0.292019712	H	1.11	0.83	2.89	3.72
0.797861378	M	2.22	0.67	5.11	5.78
0.225440748	H	1.11	0.83	6.22	7.05
0.154006941	H	1.78	0.83	8	8.83
0.384535702	H	1.78	0.83	9.78	10.61
0.91914877	M	2.22	0.67	12	12.67
0.851088928	M	1.78	0.67	13.78	14.45

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.217287822	H	1.11	0.83	0	0.67
0.948424591	M	2.22	0.67	2.22	2.89
0.10286865	H	1.11	0.83	3.33	4.16
0.146578458	H	1.78	0.83	5.11	5.94
0.953383828	M	2.22	0.67	7.33	8
0.30531581	H	1.11	0.83	8.44	9.27
0.429737202	H	1.78	0.83	10.22	11.05
0.948864888	M	2.22	0.67	12.44	13.11
0.687041646	M	1.78	0.67	14.22	14.89
0.072577082	H	1.11	0.83	15.33	16.16

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.116178814	H	0	0.83	0	0.83
0.693987782	M	2.22	0.67	2.22	2.89
0.834112979	M	1.78	0.67	4	4.67
0.548933187	M	1.78	0.67	5.78	6.45
0.325830184	H	1.11	0.83	6.89	7.72
0.14109043	H	1.78	0.83	8.67	9.5
0.67844696	M	2.22	0.67	10.89	11.56
0.676289327	M	1.78	0.67	12.67	13.34
0.274271645	H	1.11	0.83	13.78	14.61
0.00547782	S	3.96	0.5	17.74	18.24

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.446695081	M	0	0.67	0	0.67
0.882594066	M	1.78	0.67	1.78	2.45
0.37334646	H	1.11	0.83	2.89	3.72
0.401929421	H	1.78	0.83	4.67	5.5
0.922222356	M	2.22	0.67	6.89	7.56
0.080140956	H	1.11	0.83	8	8.83
0.799432253	M	2.22	0.67	10.22	10.89
0.955690595	M	1.78	0.67	12	12.67
0.77503636	M	1.78	0.67	13.78	14.45
0.773257125	M	1.78	0.67	15.56	16.23

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.098439019	H	0	0.83	0	0.83
0.172451757	H	1.78	0.83	1.78	2.61
0.342141093	H	1.78	0.83	3.56	4.39
0.352818019	H	1.78	0.83	5.34	6.17
0.455460093	M	2.22	0.67	7.56	8.23
0.77302165	M	1.78	0.67	9.34	10.01
0.330482458	H	1.11	0.83	10.45	11.28
0.873842637	M	2.22	0.67	12.67	13.34
0.748953593	M	1.78	0.67	14.45	15.12
0.000239771	S	3.4	0.5	17.85	18.35

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.423289943	H	0	0.83	0	0.83
0.315707567	H	1.78	0.83	1.78	2.61
0.2604288	H	1.78	0.83	3.56	4.39
0.681183226	M	2.22	0.83	5.78	6.61
0.399734458	H	1.11	0.83	6.89	7.72
0.109407458	H	1.78	0.83	8.67	9.5
0.426349918	H	1.78	0.83	10.45	11.28
0.664895517	M	2.22	0.67	12.67	13.34
0.482857485	M	1.78	0.67	14.45	15.12
0.024039495	H	1.11	0.83	15.56	16.39

10 “Warm up” samples of Monte Carlo simulation for departures on 20R

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.360700265	H	0	0.83	0	0.83
0.230734317	H	2.67	0.83	2.67	3.5
0.13543879	H	2.67	0.83	5.34	6.17
0.645507086	M	3.11	0.83	8.45	9.28
0.944717298	M	1.78	0.83	10.23	11.06
0.883795482	M	1.78	0.83	12.01	12.84
0.129330905	H	1.11	0.83	13.12	13.95
0.201303362	H	2.67	0.83	15.79	16.62
0.118515867	H	2.67	0.83	18.46	19.29

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.159217487	H	0	0.83	0	0.83
0.848322823	M	3.11	0.83	3.11	3.94
0.110428734	H	1.11	0.83	4.22	5.05
0.191778457	H	2.67	0.83	6.89	7.72
0.707991838	M	3.11	0.83	10	10.83
0.781636504	M	1.78	0.83	11.78	12.61
0.52364754	M	1.78	0.83	13.56	14.39
0.698366021	M	1.78	0.83	15.34	16.17
0.421734268	H	1.11	0.83	16.45	17.28
0.520821455	M	3.11	0.83	19.56	20.39

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.081650083	H	0	0.83	0	0.83
0.027409174	H	2.67	0.83	2.67	3.5
0.351001921	H	2.67	0.83	5.34	6.17
0.764989275	M	3.11	0.83	8.45	9.28
0.846214853	M	1.78	0.83	10.23	11.06
0.687909848	M	1.78	0.83	12.01	12.84
0.989100672	M	1.78	0.83	13.79	14.62
0.836028924	M	1.78	0.83	15.57	16.4
0.142872789	H	1.11	0.83	16.68	17.51
0.182919529	H	2.67	0.83	19.35	20.18

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.551288786	M	0	0.83	0	0.83
0.565200196	M	1.78	0.83	1.78	2.61
0.135489566	H	1.11	0.83	2.89	3.72
0.161056577	H	2.67	0.83	5.56	6.39
0.812635175	M	3.11	0.83	8.67	9.5
0.698602091	M	1.78	0.83	10.45	11.28
0.053280613	H	1.11	0.83	11.56	12.39
0.676165129	M	3.11	0.83	14.67	15.5
0.169928247	H	1.11	0.83	15.78	16.61
0.6972812	M	3.11	0.83	18.89	19.72

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.821482384	M	0	0.83	0	0.83
0.133938203	H	1.11	0.83	1.11	1.94
0.487095908	M	3.11	0.83	4.22	5.05
0.068889104	H	1.11	0.83	5.33	6.16
0.025856854	H	2.67	0.83	8	8.83
0.367343953	H	2.67	0.83	10.67	11.5
0.746171297	M	3.11	0.83	13.78	14.61
0.468369221	M	1.78	0.83	15.56	16.39
0.384736091	H	1.11	0.83	16.67	17.5
0.412563365	H	2.67	0.83	19.34	20.17

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.300107478	H	0	0.83	0	0.83
0.589064962	M	3.11	0.83	3.11	3.94
0.752834674	M	1.78	0.83	4.89	5.72
0.619518634	M	1.78	0.83	6.67	7.5
0.686136862	M	1.78	0.83	8.45	9.28
0.03544659	H	1.11	0.83	9.56	10.39
0.996451582	M	3.11	0.83	12.67	13.5
0.360554669	H	1.11	0.83	13.78	14.61
0.370175125	H	2.67	0.83	16.45	17.28
0.882448635	M	3.11	0.83	19.56	20.39

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.26457617	H	0	0.83	0	0.83
0.69528543	M	3.11	0.83	3.11	3.94
0.073438854	H	1.11	0.83	4.22	5.05
0.35101697	H	2.67	0.83	6.89	7.72
0.999809012	M	3.11	0.83	10	10.83
0.455036171	M	1.78	0.83	11.78	12.61
0.556866052	M	1.78	0.83	13.56	14.39
0.964477998	M	1.78	0.83	15.34	16.17
0.398273026	H	1.11	0.83	16.45	17.28

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.218901385	H	2.67	0.83	0	0.83
0.659360789	M	3.11	0.83	3.11	3.94
0.927774175	M	1.78	0.83	4.89	5.72
0.966872882	M	1.78	0.83	6.67	7.5
0.644871762	M	1.78	0.83	8.45	9.28
0.365202093	H	1.11	0.83	9.56	10.39
0.297054728	H	2.67	0.83	12.23	13.06
0.207089212	H	2.67	0.83	14.9	15.73
0.467268801	M	3.11	0.83	18.01	18.84
0.88309236	M	1.78	0.83	19.79	20.62

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.585343031	M	1.78	0.83	0	0.83
0.249742517	H	1.11	0.83	1.11	1.94
0.920308668	M	3.11	0.83	4.22	5.05
0.657557856	M	1.78	0.83	6	6.83
0.965325952	M	1.78	0.83	7.78	8.61
0.482420725	M	1.78	0.83	9.56	10.39
0.342925146	H	1.11	0.83	10.67	11.5
0.640330995	M	3.11	0.83	13.78	14.61
0.05791637	H	1.11	0.83	14.89	15.72
0.738662483	M	3.11	0.83	18	18.83

Random Number	Aircraft Type	Sep Interval	Run Occ	EnterRun	ExtRun
0.136400818	H	1.11	0.83	0	0.83
0.251059302	H	2.67	0.83	2.67	3.5
0.460391458	M	3.11	0.83	5.78	6.61
0.637948975	M	1.78	0.83	7.56	8.39
0.957958504	M	1.78	0.83	9.34	10.17
0.405886408	H	1.11	0.83	10.45	11.28
0.274116704	H	2.67	0.83	13.12	13.95
0.192632251	H	2.67	0.83	15.79	16.62
0.995595	M	3.11	0.83	18.9	19.73
0.209034127	H	1.11	0.83	20.01	20.84