GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

ANALYSIS IN AIRFIELD CAPACITY AND DELAY

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Madrid

Julio de 2019

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Fdo.: Juan-Lorenzo de Navascués Gómez Fecha: 09/ 07/2019

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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

ANALYSIS IN AIRFIELD CAPACITY AND DELAY

Autor: Juan Lorenzo de Navascués Gómez

Director: Paul M. Schonfeld

Madrid

Julio de 2019

ÁNALISIS DE LA CAPACIDAD AÉREA Y TIEMPO DE ESPERA PARA ATERRIZAJES BASADOS EN EL MÉTODO DE GRUPOS

Autor: **Navascués Gómez, Juan Lorenzo de.**

Director: Schonfeld, Paul M.

Entidad Colaboradora: University of Maryland / ICAI – Universidad Pontifica Comillas.

RESUMEN DEL PROYECTO

Introducción:

La industria aérea está experimentando un continuo crecimiento y desarrollo a nivel mundial. El número de pasajeros y vuelos que se producen diariamente aumenta año tras año. De acuerdo a la Administración Federal de Aviación de los Estados Unidos (FAA), la aviación y en especial, el flujo de pasajeros ha experimentado un crecimiento constante durante los últimos 10 años y se espera que continúe en el futuro próximo. Además, cálculos y estudios realizados por la Asociación Internacional de Transporte Aéreo (IATA) pronostican que, siguiendo la tendencia de los últimos años, en 2037 el número de pasajeros podría doblarse hasta los 8.200 millones.

Esta evolución y aumento de la demanda exige a los aeropuertos un continuo desarrollo y evolución para poder hacer frente a las nuevas necesidades. Sin embargo, los aeropuertos no pueden crecer ni aumentar el tamaño de sus instalaciones de igual manera y velocidad que la demanda. Por esto, paralelamente a este crecimiento se está produciendo el aumento en niveles de tráfico aéreo generando un mayor número de situaciones de congestión aérea[1]. De este modo, los aeropuertos además de realizar las mejoras necesarias y alcanzables en términos de infraestructura e instalaciones, necesitarán modificar y analizar sus modelos operativos para hacer frente a este crecimiento y mejorar en otros aspectos como la capacidad aeroportuaria[2].

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[1] Un aeropuerto se encuentra en congestión aérea cuando no es capaz de realizar el número de operaciones (despegues y/o aterrizajes) demandadas en un determinado intervalo de tiempo.

[2] La capacidad aeroportuaria se define como el rendimiento máximo sostenible de las operaciones de aterrizajes y/o despegues que se pueden lograr en un intervalo de tiempo específico con un nivel de retraso aceptable.

Por todo lo anterior, este proyecto se centra en analizar y determinar si el modelo de operación utilizado en la distribución de aeronaves en el momento de aterrizaje puede verse mejorado por los aterrizajes basados en el método de grupos.

Actualmente los aeropuertos operan siguiendo el First-Come, First-Serve (F.C.F.S.) que se basa en otorgar permiso para aterrizar a las aeronaves según el orden en el que éstas lo piden. Como resultado, surge un orden completamente aleatorio de aeronaves aterrizando sin tener en cuenta tamaños y velocidades de acercamiento. La Organización de Aviación Civil Internacional (ICAO) divide las aeronaves en 4 grupos diferentes teniendo en cuenta su velocidad de aproximación y el vórtice que generan:

Tipo de Aeronave	**Velocidad de acercamiento (KNOTS)**	**Velocidad Máxima para Circling**	**Vórtice Generado**	**Aeronave Tipica**
A	<91	100	Small	Small Single engine
B	91-120	135	Small	Small Multi engine
C	121-140	180	Large	Airline Jet
D	141-165	205	Heavy	Large Jet/Military Jet

Tabla 1 Clasificación de Aeronaves según Velocidad de Acercamiento y Vórtice Fuente: ICAO

Aunque el FCFS no considera el tipo de aeronave entrante, las regulaciones existentes sí determinan un espacio mínimo de seguridad entre cada aterrizaje que depende principalmente del tamaño y vórtice generado por el aterrizaje precedente. De acuerdo a la regulación estadounidense, estas distancias (en millas náuticas) deben ser:

	Nautical Miles	**Trailing Aircraft**		
		Heavy	**Large**	**Small**
Leading Aircraft	**Heavy**	4	5	5/6*
	Large	2.5 (or 3)	2.5 (or 3)	3/4*
	Small	2.5 (or 3)	2.5 (or 3)	2.5 (or 3)

Tabla 2 Separación Mínima entre aterrizajes consecutivos Fuente. FAA

Como consecuencia, el FCFS no optimiza el orden de llegada de tal forma que se produzca el mínimo tiempo entre dos aterrizajes consecutivos y reducir así el tiempo total de operaciones.

El método de grupos se basa en realizar los aterrizajes en ciclos de intervalos de escuadrones de aviones según su tamaño y/o velocidad de aproximación. De esta manera, se busca conseguir reducir al máximo el número de aterrizajes que preceden a aeronaves de diferente categoría. Como resultado, se obtendría un mayor número de operaciones alcanzables y se reducirían las situaciones de congestión aérea.

El siguiente diagrama espacio tiempo muestra un cómo sería un ciclo del FCFS y cómo sería un ciclo del método de escuadrones:

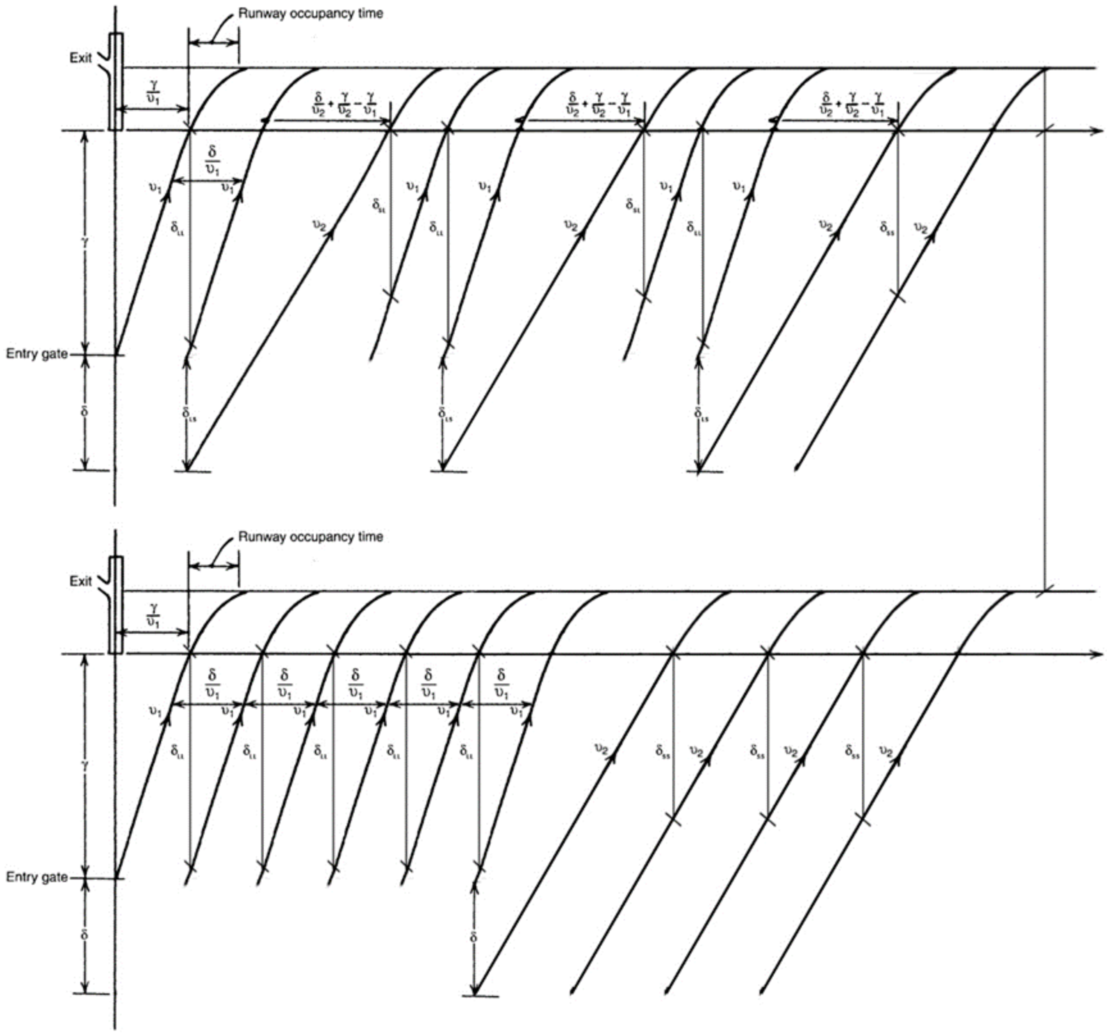

Figura 1 Comparación de llegadas siguiendo el FCFS y el método de grupos. Fuente: Elaboración Propia

Metodología:

El objetivo de este proyecto es determinar si como primer análisis, el método basado en grupos proporciona mejores resultados en términos de capacidad que los obtenidos con el FCFS. Para conseguir este análisis, se ha desarrollado la formulación para el método basado en grupos considerando velocidades de aproximación, separaciones mínimas de acuerdo a la regulación y probabilidades de aeronaves de acuerdo a las establecidas por la FAA. Además, se ha analizado también como afectaría al tiempo medio de retraso la incorporación de este método desarrollando una formulación basada en la probabilidad de que cada grupo se encuentre en su turno de aterrizaje y tiempo medio de espera. Todos estos cálculos, se han comparado con los resultados del FCFS para los mismos escenarios. Para los cálculos del FCFS se ha seguido la formulación establecida por (Norman J. Ashford, 2011) y para el cálculo del tiempo de retraso medio, se utilizó la fórmula de Pollaczek–Khinchine[3]. Como herramienta de resolución para los diferentes casos analizados, se ha utilizado Excel introduciendo todas las variables y constantes determinantes. Además, se ha desarrollado una macro en Excel que contiene dos programas de análisis. El primero permite al usuario introducir una serie de datos específicos en relación a la velocidad de acercamiento y el número de mezclas de aeronaves que quiere comparar. Como resultado, el programa generará X mezclas de aeronaves aleatorias, y comparará los resultados con los del FCFS otorgando como salida gráficos de comparación entre los dos métodos. El segundo programa, permite al usuario introducir 3 casos específicos que quiera comparar o comprobar diferencias y proporciona como salida una matriz de gráficos en la que se muestra los análisis más importantes.

En este proyecto, se ha analizado también la posibilidad de añadir despegues entre medias de los aterrizajes del método de grupos lo que proporcionaría un aumento extra en la capacidad del aeropuerto. Todos los escenarios y cálculos se han realizado para aeropuertos con una pista de aterrizaje como el Aeropuerto Internacional de San Diego:

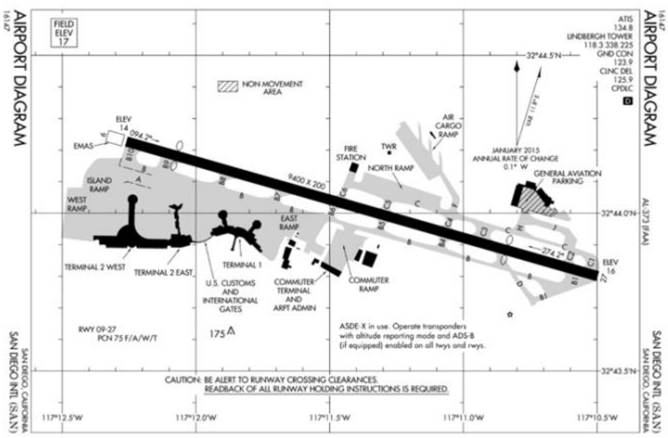

Figura 2 Plano Aeropuerto Internacional de San Diego Fuente: FAA

[3]La fórmula de Pollczek-Khinchine, establece una relación entre la longitud media de la cola y el tiempo medio de espera o servicio del modelo analizado

Resultados:

Caso Base:

- 2 tipos de aviones y Aircraft Mix A:40% B:0% C:60% D:0%
- 4 tipos de aviones y Aircraft Mix A:20% B:40% C:20% D:20%

En este caso base se realizaron los análisis y comparación entre las mezclas de aeronaves anteriormente expuestas y se obtuvieron los siguientes resultados:

(Cabe mencionar que "Mixed Arrivals" hace referencia al FCFS y "Grouping Method" al método basado en escuadrones o grupos de aviones).

Capacidad:

Aircraft Mix	Mixed Arrivals	Grouping Method
A:40% B:0% C:60% D:0%	30.53 ops/hour	40.51 ops/hour
A:20% B:40% C:20% D:20%	31.40 ops/hour	34.53 ops/hour

Tabla 3 Resultados para la Capacidad Caso Base

Tiempo de espera medio:

Aircraft Mix	Mixed Arrivals	Grouping Method
A:40% B:0% C:60% D:0%	25.35 secs/op	42.8 secs/op
A:20% B:40% C:20% D:20%	26.57 secs/op	45.35 secs/op

Tabla 4 Resultados tiempo de espera medio Caso Base

Despegues Intermedios Aterrizajes:

Aircraft Type		Leading Aircraft	
		A	**C**
Trailing Aircraft	**A**	NO	SÍ
	C	NO	NO

Tipo de Aeronave		Avión Precedente			
		A	**B**	**C**	**D**
Avión que Sigue	A	NO	SÍ	SÍ	SÍ
	B	NO	NO	SÍ	SÍ
	C	NO	NO	NO	SÍ
	D	NO	NO	NO	NO

Tabla 5 Resultados Despegues Caso Base

Extensión Caso Base:

Como extensión del caso base, se procedió a realizar un análisis de 5 escenarios diferentes que representan de una manera más fiable los resultados del método basado en escuadrones. Los 5 escenarios se eligieron de acuerdo a la formulación de la FAA. Los resultados de la comparación entre los 5 escenarios con el método de escuadrones y el FCFS pueden verse en los gráficos siguientes:

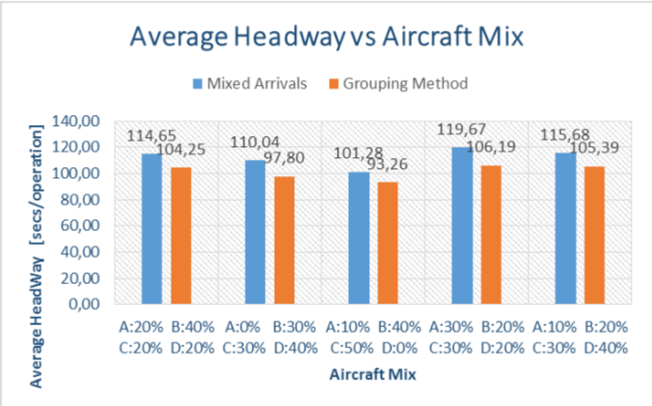

Figura 4 Frecuencia Media de Aterrizajes VS Mezcla de Aviones

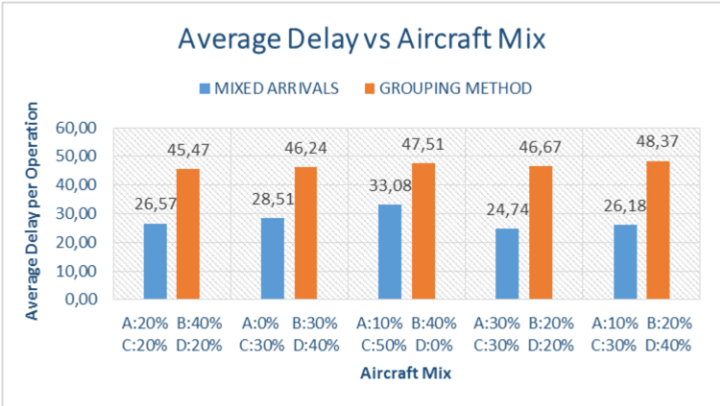

Figura 3 Tiempo Medio de Espera VS Mezcla de Aviones

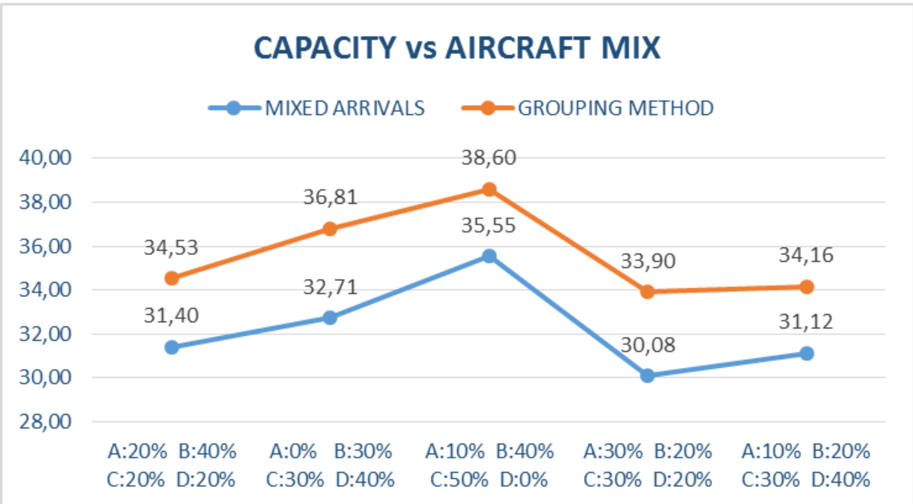

Figura 5 Capacidad VS Mezcla de Aviones

Además, se realizó un estudio sobre la influencia que tiene el tamaño del ciclo dentro del método de escuadrones. Es decir, cómo influye el número de aviones que aterrizan por cada ciclo del método de escuadrones.

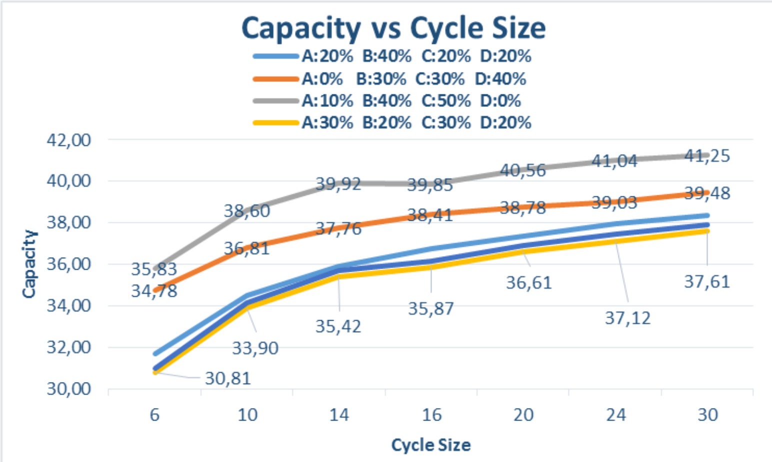

Figura 6 Capacidad VS Aterrizajes por ciclo

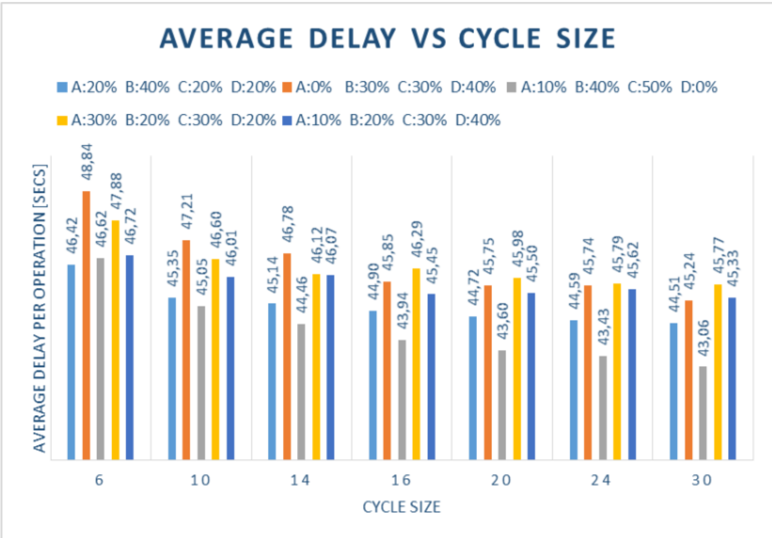

Figura 7 Tiempo medio de espera VS Aviones por ciclo

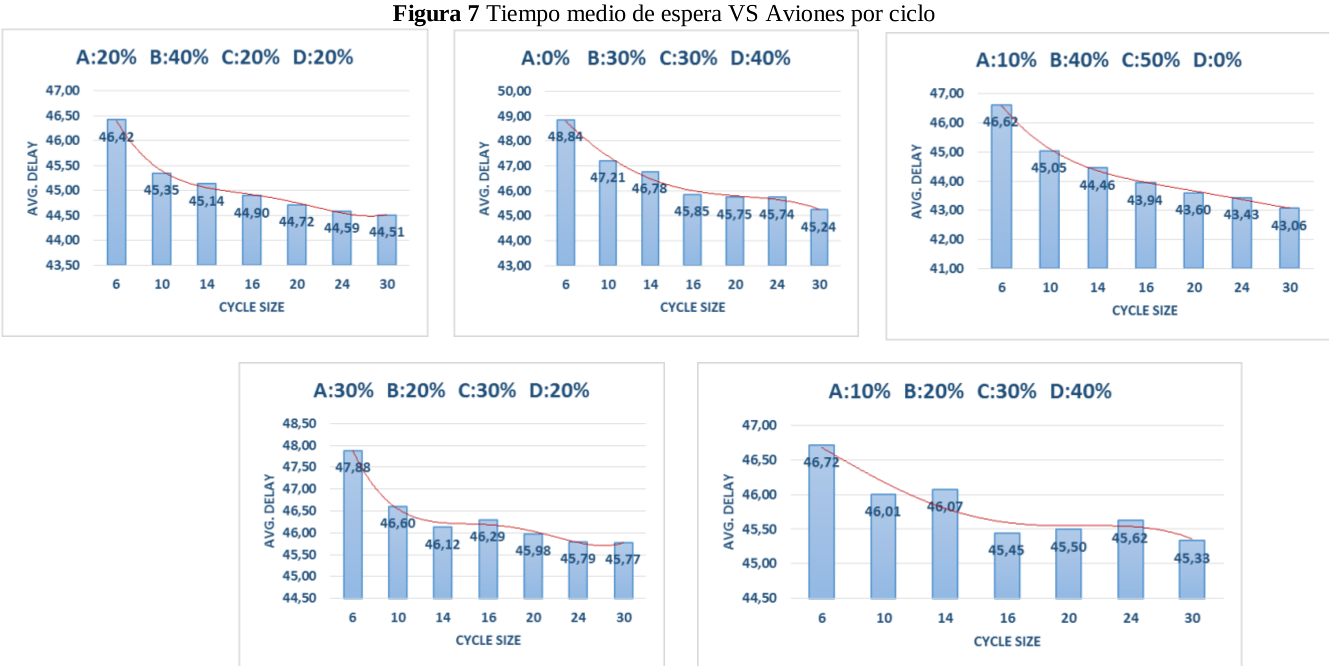

Figura 8 Análisis individual tiempos de espera medios VS Aviones por ciclo para cada escenario

Conclusiones:

La industria de la aviación va a tener que hacer frente a un continuo aumento de la demanda que supondrá una mayor exigencia a los aeropuertos en todos los ámbitos. Con los resultados del análisis realizado en este proyecto, se puede concluir que una primera solución para enfrentarse a las situaciones de congestión aérea es la aplicación del método de grupos/escuadrones de aviones y la aplicación de los despegues entre aterrizajes consecutivos. No obstante, en vista de los resultados obtenidos, la aplicación de este nuevo método no tiene sentido en situaciones no congestionadas. En todos los casos analizados tanto en este proyecto como en la herramienta Excel desarrollada, la capacidad aeroportuaria aumenta con el método de escuadrones pero el tiempo medio de espera también lo hace, provocando que el FCFS sea el mejor método para situaciones de no congestión (pues la demanda es inferior a la capacidad que éste puede ofrecer).

Como conclusión final, se debe decir que el método de escuadrones o grupos supone en primera instancia, una mejora de la capacidad en todos los niveles. Por ello, debería ser analizado con la tecnología y software utilizados en las instalaciones de los aeropuertos. Asimismo, sería óptimo desarrollar un software que permitiese a los controladores cambiar de método de forma dinámica en el momento en el que se necesite hacer frente a una demanda mayor de la alcanzable por el FCFS y la utilización del método de escuadrones fuese mejor. Cabe decir que en este análisis se han realizado aproximaciones razonables y por tanto, los futuros análisis que se realicen con instrumentos y tecnología real deberían considerar todos los factores adyacentes como taxiways, touchdowns, o aproximaciones erróneas.

ANALYSIS IN AIRFIELD CAPACITY AND DELAY FOR THE GROUPING METHOD

Introduction:

The aviation industry is experiencing constant growth and development worldwide. The number of passengers and flights increases from year to year. According to the FAA (Federal Aviation Administration), aviation and , in particular, passenger flow have been growing at a constant rate for the last 10 years and this growth is expected to continue for the upcoming future. Furthermore, IATA (International Air Traffic Transportation) forecast shows that present trends in air transportation suggest passenger flow could double actual levels rising them up to 8.2 billion in 2037.

This growth in passenger flow will make major changes in demand, forcing airports to continuously develop improvements to meet the growing demand. However, airports cannot modify its layout, or increase their area at the same speed as the demand grows. This situation leads us to a scenario where air traffic keeps growing resulting in more congested periods for the airports. In this way, airports will need to modify and update their operating systems to face this demand by increasing its actual airfield capacity.

In this light, this Project is focused on analyzing and determining whether the actual operating system used for landings could be improved by arrivals following the grouping method.

Currently, airports operate landings following the First-Come, First-Serve (FCFS) method basis where aircraft lands according to the order in which they have asked for permission. This method is probably the most effective and the best one for non-congested periods. However, at times when the airports are suffering from air traffic congestion (which will be very likely to happen at the growth rates we are currently experiencing), there is room for improvement in the FCFS, as we will discuss in this paper.

As a result of this method, a completely random order of arrivals come up without considering aircraft size or approaching speeds. According to ICAO (International Civil Aviation Organization), there are 4 different aircraft class considering its approaching speed and maximum take-off weight (MTOW) classification:

Aircraft Class	**Approaching speed V_{AT} (KNOTS)**	**Maximum speeds for circling**	**Wake Turbulence Classification**	**Typical aircraft in this category**
A	<91	100	Small	Small Single engine
B	91-120	135	Small	Small Multi engine
C	121-140	180	Large	Airline Jet
D	141-165	205	Heavy	Large Jet/Military Jet

Table 1 Aircraft Classification According Approaching Speed Source: ICAO

Although the FCFS does not consider the aircraft classification of the upcoming arrival, existing regulations established by the FAA determine a minimum safety separation between two consecutive landings according to its classification and wake vortex generated:

	Nautical Miles	**Trailing Aircraft**		
		Heavy	**Large**	**Small**
Leading Aircraft	**Heavy**	4	5	5/6*
	Large	2.5 (or 3)	2.5 (or 3)	3/4*
	Small	2.5 (or 3)	2.5 (or 3)	2.5 (or 3)

Table 2 Minimum Safety Separation between two consecutive Arrivals Source:FAA

As a result, the FCFS does not optimize the arrival order in a way which the time between two consecutive arrivals is the minimum and reducing the total operational time per cycle. On the other hand, the grouping method will divide the upcoming arrivals into cycles of platoons of the same aircraft class and approach speed in order to reduce the time between each. In consequence, the airfield capacity would increase and the number of congested periods would become lower.

The following time-space diagram compares how a landing cycle would be using the FCFS and the grouping method for two different types of aircraft.

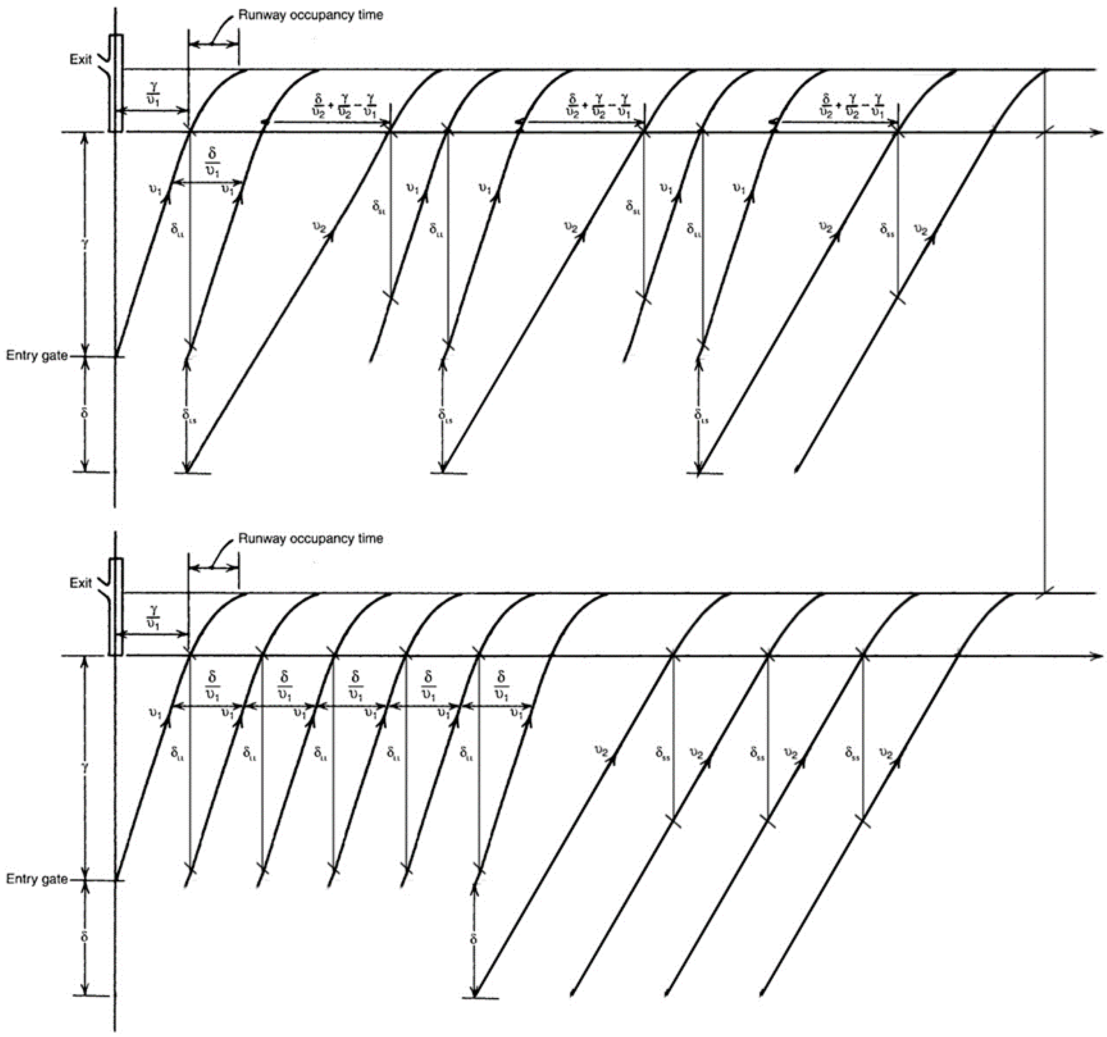

Figure 1 Time-Space diagram for FCFS & the Grouping Method Source:Prepared by the author

Methodology:

The ultimate goal of this paper is to determine as a first approach, whether the grouping method provides better results in airfield capacity than the FCFS or not. To achieve this, we have developed the formulation for this method considering approaching speeds, minimum safety separations, and aircraft mix according to the FAA regulations. In addition, the average delay this method would cause has been analyzed and properly compared to the FCFS. For this formulation, it has been assumed a total waiting time of half of the duration of its platoon in the case the plane arrives at the same time its platoon has obtained permission to begin landing. Otherwise, if the plane arrives when a different group is landing, it will have to wait for the duration of all the others platoons plus half of its own. This a simple and conservative way of calculating the average delay that will give us a reasonable approach and comparison to the mixed one. For the FCFS calculations, it has been used the Pollaczek–Khinchine queuing theory. All calculations have been computed by means of Excel. Additionally, two programs have been coded in Excel. In the first one, the user inputs the specific data (approaching speed, length of common approach) and the number of different he wants to analyze. As a result, the program will output three charts comparing the different aircraft mixes using the Grouping Method to the FCFS. The second program allows the user to input three specific mixes and it will output nine charts to compare the results between them and the FCFS.

In this project, the possibility of incorporating take-offs between two consecutive landings in the grouping method has been also analyzed. In the cases where this is reachable, it will mean an extra addition in terms of airfield capacity. All calculations and scenarios alongside this paper have been computed for an airport of one runway (i.e. San Diego Int. Airport).

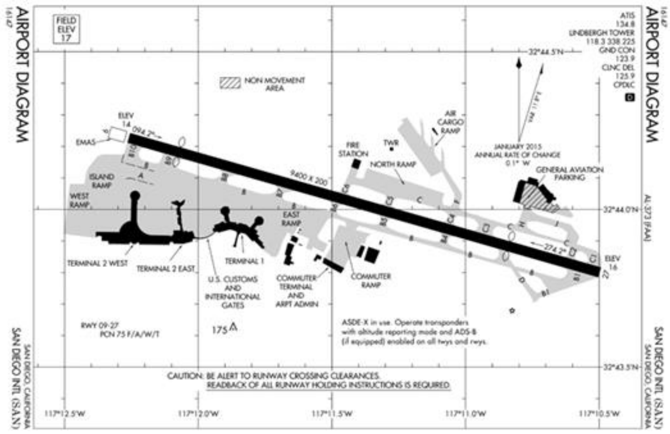

Figure 2 San Diego International Airport Layout Source:FAA

Results:

Case Study:

- 2 Aircraft Types & Aircraft Mix A:40% B:0% C:60% D:0%
- 4 Aircraft Types & Aircraft Mix A:20% B:40% C:20% D:20%

In this initial case, the above-stated aircraft mixes have been analyzed to establish a comparison between the two methods of allocating arrivals:

Capacity:

Aircraft Mix	Mixed Arrivals	Grouping Method
A:40% B:0% C:60% D:0%	30.53 ops/hour	40.51 ops/hour
A:20% B:40% C:20% D:20%	31.40 ops/hour	34.53 ops/hour

Table 3 Capacity Results for the Case Study

Average Delay:

Aircraft Mix	Mixed Arrivals	Grouping Method
A:40% B:0% C:60% D:0%	25.35 secs/op	42.8 secs/op
A:20% B:40% C:20% D:20%	26.57 secs/op	45.35 secs/op

Table 4 Average Delay Results for the Study Case

Takeoffs between Consecutive Landings:

Aircraft Type		Leading Aircraft	
		A	**C**
Trailing Aircraft	**A**	NO	YES
	C	NO	NO

Aircraft Type		Leading Aircraft			
		A	**B**	**C**	**D**
Trailing Aircraft	A	NO	YES	YES	YES
	B	NO	NO	YES	YES
	C	NO	NO	NO	YES
	D	NO	NO	NO	NO

Table 5 In-between Takeoffs Results for the Case Study

Case Study Extension:

As an extension for the basic case, an analysis for 5 different scenarios was developed in order to obtain a more representative image of the influence the grouping method would have. All 5 scenarios were selected according to the FAA formulation. The results obtained can be seen in the following charts:

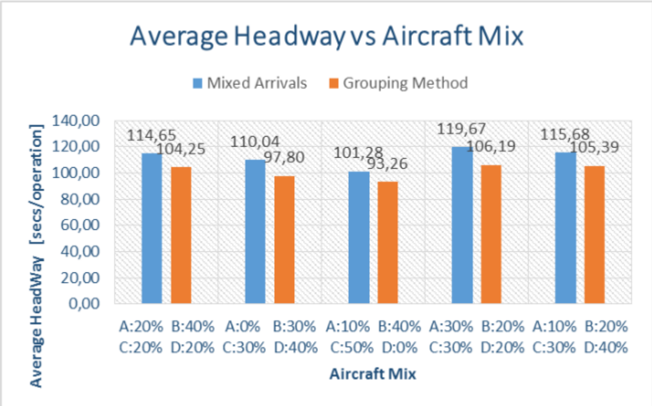

Figure 4 Average Headway vs Aircraft Mix

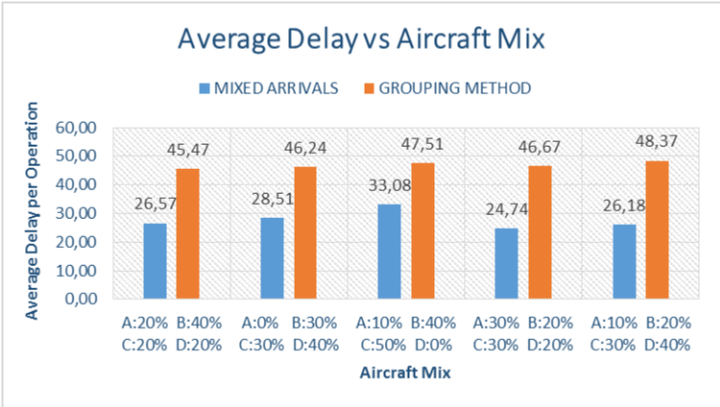

Figure 3 Average Delay vs Aircraft Mix

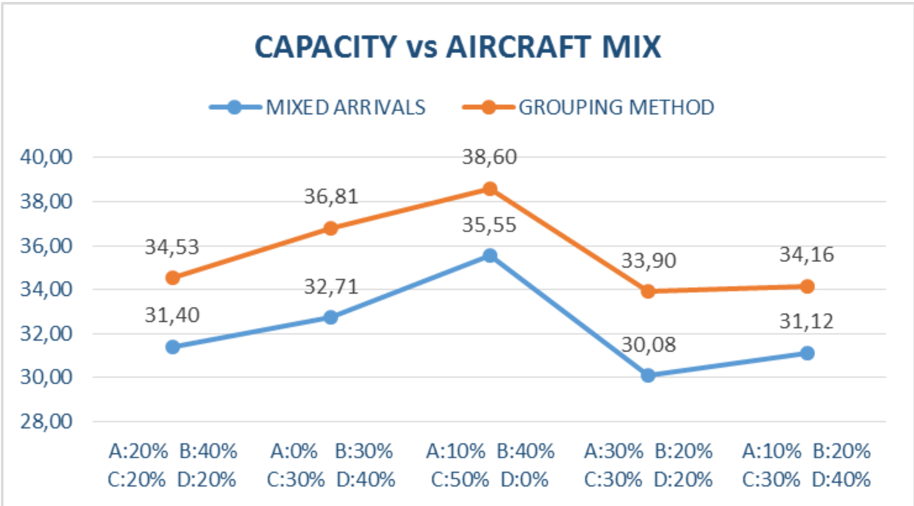

Figure 5 Capacity vs Aircraft Mix

In addition, the influence the cycle size has in the grouping method was analyzed:

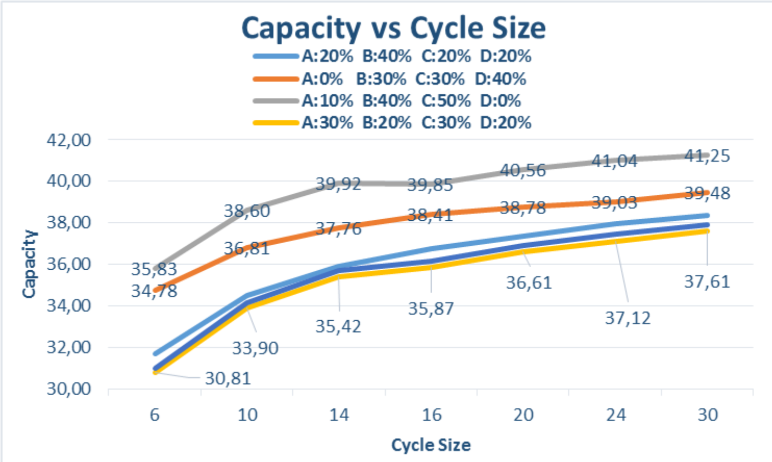

Figure 6 Capacity vs Cycle Size

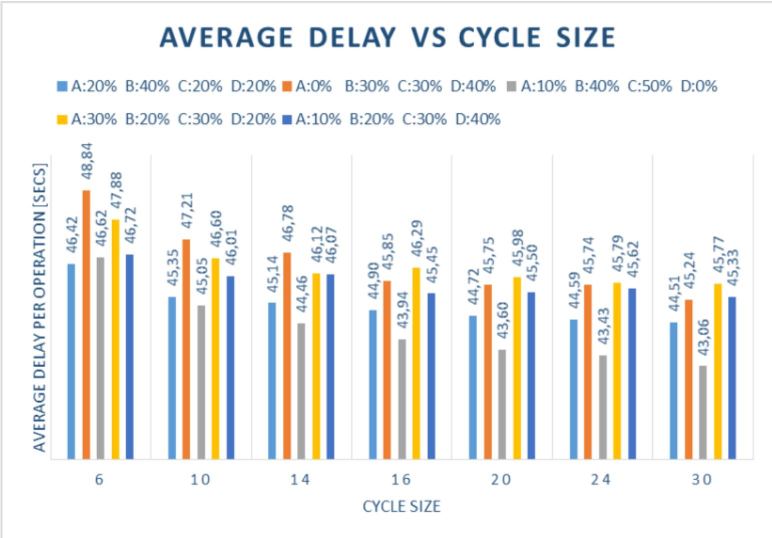

Figure 7 Average Delay vs Cycle Size

Figure 8 Average Delay Indiviual Scenario Analysis vs Cycle Size

Conclusions:

The aviation industry will have to face a continuous increase in demand that will require important upgrades in airports at all levels. After the results obtained in this paper, it can be concluded that the grouping method could be one solution for the upcoming congested periods. In all cases studied in this paper and solved with the program developed, the grouping method obtains better results in terms of airfield capacity. However, it has to be said that in non-congested periods the application of this technique will not make sense it provides greater average delay than the FCFS.

As a final conclusion, the grouping method results are at first approach, good enough for taking it into consideration for further research on this field. It should be analyzed and optimized using software and technologies available at airports. In addition, it would be optimal to develop a program that allows air traffic controllers to dynamically switch between both methods whenever the FCFS cannot afford the demand levels.

MEMORIA

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ABSTRACT

According to the FAA, Aviation and especially passenger flow has been consistently growing for the last 10 years and it is expected to continue with this growth (Federal Aviation Administration, 2019). Alongside this growth, airports and aviation resources are likely to reach its full operational potential in the next years making progress and development a priority. The ultimate goal of this paper is to study the viability of using a group method for landings in order to obtain a greater value of the airfield capacity. It specifically deals with a comparison between the actual method used in airports when they are experiencing take-offs & landings (FCFS), and a possible platoon-based method that could be adopted by the airports. In this paper, the formulation of the capacity & average delay for the grouping method has been developed and the sensitivity analysis completed shows that there is room for improvement in terms of capacity. The grouping method would increase the capacity in comparison to the (FCFS). However, it leads to a larger average delay meaning that there will be periods where it would be reasonable to adopt this technique when delay is not a concern and capacity is more important.

INTRODUCTION

Airfield or runway capacity is defined as the maximum sustainable throughput of aircraft operations, i.e. both arrivals and departures that can be achieved during a specified time interval (e.g. 1 hour) at a given airport with a specific runway layout, under different weather conditions, and at an acceptable level of delay. It indicates the average number of movements that can be performed on the runway system in 1 hour in the presence of continuous demand while meeting all the requirements imposed by the corresponding Aviation Administration (FAA in the USA) and air traffic management (ATM) system. The capacity of the airfield and especially of the runway typically determines the ultimate capacity of an airport.

There has been a great research during the past five decades on computing this airfield capacity as well as determining new methods to define and measure it. Air traffic demand is one important factor when determining the capacity as it determines whether an airport is congested or not at any time. An important variable in this relationship, is the mean departure/arrival rate which is defined as the safely permissible interoperation time for arrivals and departures.

According to a new report from the International Air Transport Association (IATA), passenger numbers are likely to surge in the next couple of decades. IATA expects 8.2 billion passengers to travel by air in 2037, a near doubling of today's 3.8 billion level. *Fig.1* shows the passenger flow development of San Diego Airport from 1970 until 2018.

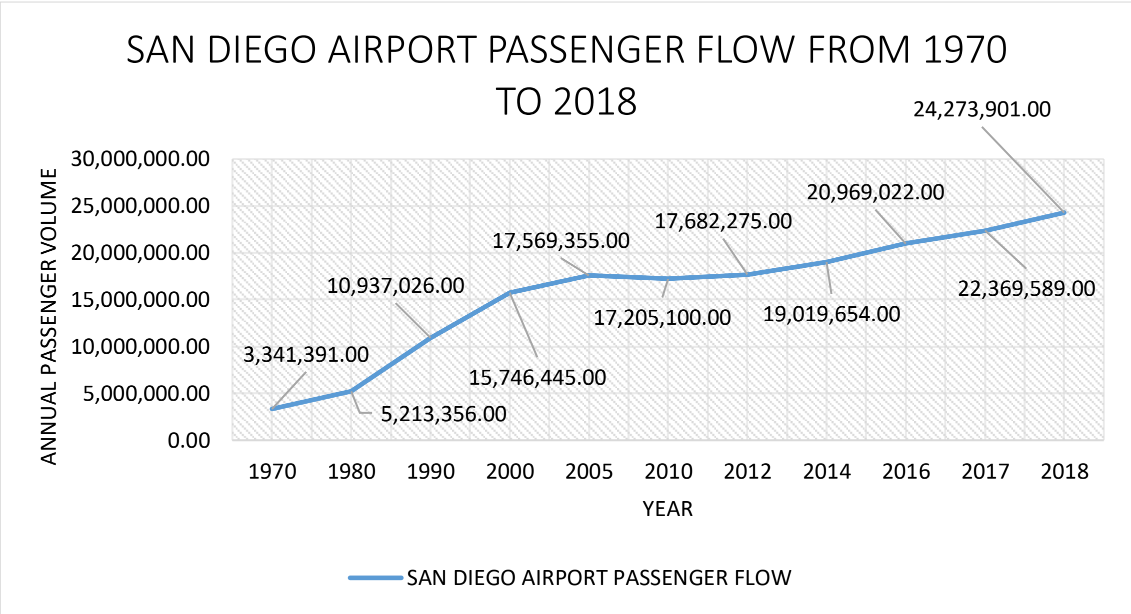


Figure 1 Passenger Flow Evolution *Data Source: FAA*

This expected doubling in air travel is placing extra strain on airports that are already creaking at the seams. New challenges include improvements in airfield capacity technologies in order to be able to maintain the passengers flow in an efficient and cost-effective way, plus satisfying the rising security standards now required worldwide.

The huge growth in terms of passenger flow leading to an increase in airfield operations justifies a review of the methods used worldwide to keep the capacity of the airports as high as possible. Nowadays, the airports operate on a first-come, first serve (FCFS) basis where the aircraft land according to the order in which they have asked for permission. This method is probably the most effective and the best one for non-congested periods. However, at times when the airports are suffering from air traffic congestion (which will be very likely to happen at the growth rates we are currently experiencing) there is room for improvement in the FCFS, as we will discuss in this paper. The method that will be analyzed in this paper is based on grouping of aircraft.

The grouping method will divide the upcoming arrivals into cycles of platoons of the same aircraft class and approach speed in order to reduce the time between each. We will study the viability of this method from a basic case of an airport with one runway (e.g. San Diego Airport) and some reasonable assumptions. It will also be analyzed the possibility of using mixed-runways in order to incorporate take-offs between following landings in the cases they meet all safety requirements imposed by the Federal Aviation Administration (FAA).

Prior to start analyzing/studying the airfield capacity, it is necessary to define some of the basic knowledge regarding aircraft types and Landing/Departures procedures. The FAA (Federal Aviation Administration) divides all aircraft in three large groups according to their maximum certified take-off weight (MTOW):

Aircraft Class	**Max. Certified T.O weight (lbs.)**	**Number of engines**	**Wake Turbulence Classification**
A	12,500 or less	Single	SMALL (S)
B		Multi	
C	12,500-300,000	Multi	LARGE (L)
D	Over 300,000	Multi	HEAVY (H)

Table 1 Aircraft Class According to MTOW & Wake Turbulence Classification Source: FAA

The FAA also identifies the Boeing 757 as an independent class because its MOTW is on the borderline between the Large and Heavy classes and it produces strong wake-vortex effects. For this study so far, we will assume this class negligible, as the number of Boeing 757 is too low compared to the other classes.

Another important classification when computing the capacity of an airfield is considering the approach speed of aircraft during landings. The following table from ICAO (International Civil Aviation Organization) sorts the aircraft according to their approach speed:

Aircraft Class	**Approaching speed V_{AT} (KNOTS)**	**Maximum speeds for circling**	**Wake Turbulence Classification**	**Typical aircraft in this category**
A	<91	100	Small	Small Single engine
B	91-120	135	Small	Small Multi engine
C	121-140	180	Large	Airline Jet
D	141-165	205	Heavy	Large Jet/Military Jet

Table 2 Aircraft Type & Corresponding Approaching Speed of Landings Source: ICAO

Separation Requirements for Aircraft Operating to/from the same runway

One of the most important factors in determining runway capacity is the minimum longitudinal separation requirements for aircraft landing or departing from the same runway. These separation requirements are usually given in units of distance or time, and are determined by the wake turbulence produced by each aircraft class. The FAA provides the following specifications for these four cases:

Single-Runway IFR Separation Requirements in the U.S.

i. Arrival followed by Arrival (A-A)

Depending on the aircraft class, the following aircraft types must be separated by at least the distance (in Nautical Miles) indicated below:

	Nautical Miles	**Trailing Aircraft**		
		Heavy	**Large**	**Small**
Leading Aircraft	**Heavy**	4	5	5/6*
	Large	2.5 (or 3)	2.5 (or 3)	3/4*
	Small	2.5 (or 3)	2.5 (or 3)	2.5 (or 3)

Table 3 Arrival followed by Arrival Separation Requirements Source: FAA

*Distances required at the time when the leading aircraft is at the threshold of the runway.

The trailing aircraft cannot touchdown on the runway until the leading aircraft is clear of the runway.

ii. **Arrival followed by Departure (A-D)**

Clearance for take-off run of the trailing aircraft is granted after the preceding landing is clear of the runway.

iii. **Departure followed by Departure (D-D*)**

Clearances for take-off runs of successive aircraft must be separated by at least the amount of time (in seconds) indicated below:

		Trailing Aircraft		
		H	**L**	**S**
Leading Aircraft	**H**	90	120	120
	L	60	60	60
	S	45	45	45

Table 4 Departure followed by Departure Safety Requirements Source: FAA

*These times shown are approximations and somewhat conservative estimates of the time separations that result in practice. There are more complicated sets of rules that must be satisfied, which will be discussed below.

iv. **Departure followed by Arrival (D-A)**

The trailing arrival (regardless of its size or class) must be at least 2 Nautical Miles away from the runway at the time when the departing aircraft begins it takeoff run. The departing aircraft must also be clear of the runway before the trailing aircraft touches down on it.

METHODOLOGY

➢ Airfield Capacity: Mixed Arrivals vs Grouping Method

We will use a landing intervals-model based in order to estimate runway capacity. This model accounts for the following factors:

I. Length of common approach path (γ).

II. Approaching speed of aircraft

III. Minimum separation requirements.

We will first compute this capacity for a random order of arrival (mixed) and then, for a cycle based method so we can analyze the difference. We will also study how much impact this grouping method would have in terms of delay when switching the number of planes in each platoon.

This model assumes error-free approaches, which means that controllers are able to deliver aircraft to the entry gate exactly at scheduled times and pilots are able to maintain the required separations, aircraft speeds, and alignments with the runway for landing accurately. Therefore, we need to define two different situations for these landings, (a) the overtaking case, in which the trailing aircraft has a speed equal or greater than the lead aircraft, and (b) the opening case, in which the approaching speed of the leading aircraft is greater than the trailing one. The following time-space diagrams show both situations for consecutive landings in one runway. (Norman J. Ashford, 2011)

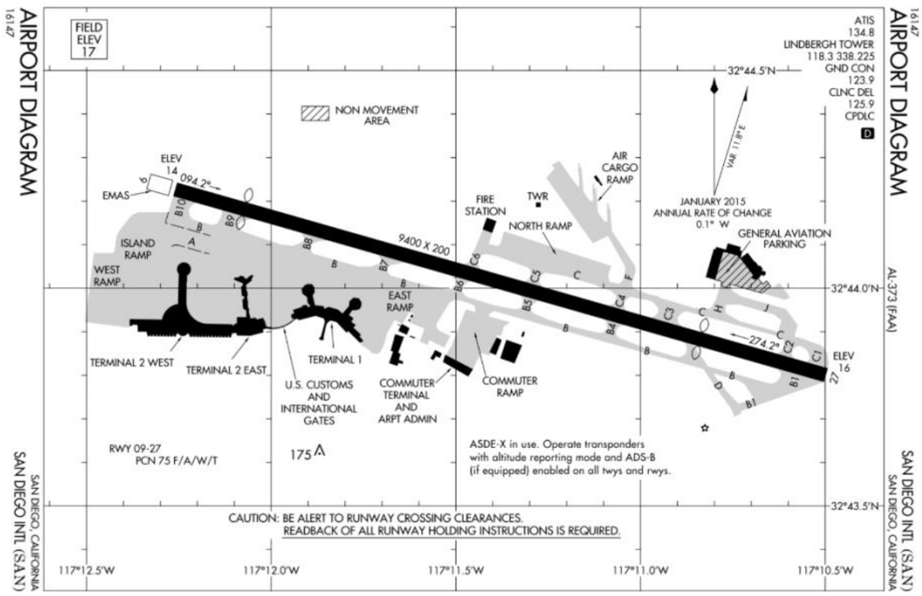


Figure 2 San Diego Airport Layout. *Source: FAA*

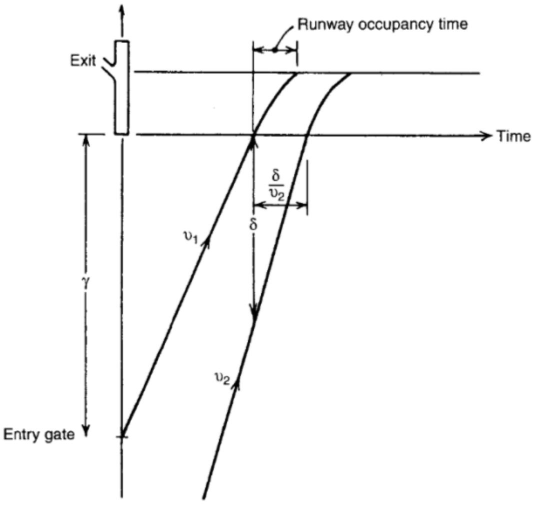


Figure 4 (a) Overtaking Case

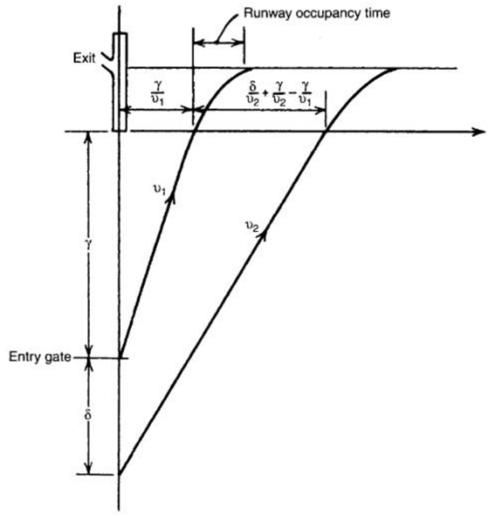


Figure 3 (b) Opening Case

The variables for this model would be:

Variable	Definition	Units
V_i	Speed of Aircraft i	$\frac{NM}{hour}$ (KNOTS)
γ	Length of Common Approach Path	NM
δ_{ij}	Safety Separation between speed class i followed by speed class j	NM
h(i,j)	Headway between leading aircraft i followed by aircraft j	Seconds
P_i	Aircraft Mix	%
h	Average Headway	Seconds
C	Capacity	$\frac{Operations}{Hour}$
N_i	Number of planes of speed class i	# Planes
ROT_i	Runway Occupancy Time for Aircraft type i	Seconds
Q_i	Platoon Size of Aircraft type i	$\frac{Planes}{Platoon}$
T	Number of Cycles	# Cycles
Z	Number of Platoons per Cycle	Platoons
D_i	Platoon duration of Aircraft type *i*	Seconds
O	Operations per Cycle	Operations

Table 5 Variables for the model

1) **Probabilities for each aircraft speed class:**

$$P_i = \frac{N_i}{\sum_{j=1}^{j=n} N_j} \text{ [Aircraft Mix]}$$

2) **Minimum Headway between landings:**

The calculation for this section varies depending on the overtaking or opening case:

- **Overtaking Case ($V_j >= V_i$)**

$$h_{ij}(Overtaking) = \frac{\delta_{ij}}{V_j} \cdot \frac{3600\ secs}{1\ hour}\ [secs] \qquad \text{For } \begin{cases} i = Leading\ Aircraft\ type \\ j = Trailing\ Aircraft\ type \end{cases}$$

- **Opening Case ($V_j < V_i$)**

$$h_{ij}(Opening) = \left(\frac{\delta_{ij}}{V_j} + \gamma \cdot \left(\frac{1}{V_j} - \frac{1}{V_i}\right)\right) \cdot \frac{3600\ secs}{1hour} [secs]\ \ for \begin{cases} i = Leading\ Aircraft\ type \\ j = Trailing\ Aircraft\ type \end{cases}$$

3) **Minimum Headway Matrix:**

Basic Case (Only accounts 2 type of Aircrafts (e.g. Small & Large)):

Trailing Aircraft (j)	**Leading Aircraft (i)**			**Probabilities (P_j)**
		Small (1)	**Large (2)**	
	Small (1)	h_{SS}	h_{LS}	P_{small}
	Large (2)	h_{SL}	h_{LL}	P_{large}
Probabilities (P_i)		P_{small}	P_{large}	

Table 6 Headway Matrix for Small & Large Planes

General Case with all Aircraft types taken into account:

Trailing Aircraft (j)	**Leading Aircraft (i)**					**Probabilities (P_j)**
		A	**B**	**C**	**D**	
	A	h_{AA}	h_{BA}	h_{CA}	h_{DA}	P_A
	B	h_{AB}	h_{BB}	h_{CB}	h_{DB}	P_B
	C	h_{AC}	h_{BC}	h_{CC}	h_{DC}	P_C
	D	h_{AD}	h_{BD}	h_{CD}	h_{DD}	P_D
Probabilities (P_i)		P_A	P_B	P_C	P_D	

Table 7 Headway Matrix for all aircraft types

4) **Total Headway:**

$$h = \sum_{i=1}^{i=n} \sum_{j=1}^{j=n} P_i \cdot h_{ij} \cdot P_j \; [Seconds]$$

5) **Capacity:**

$$h = \frac{1}{Avg\ Headway} = \frac{1}{\sum_{i=1}^{i=n} \sum_{j=1}^{j=n} P_i \cdot m_{ij} \cdot P_j} \left[\frac{Arrival}{Seconds} \cdot \frac{3600\ secs}{1\ hour}\right] \rightarrow \left[\frac{Arrivals}{Hour}\right]$$

The formulation above would allow us to estimate the capacity for a mixed sequence of arrivals without using the grouping method. As long as we want to compare the results obtained with the grouping method, we need to formulate the capacity for the grouping method as follows:

1) **Cycle Dimension Definition:**

$$1\text{ Cycle} = 1\text{ Platoon Planes type (i)} + 1\text{ Platoon Planes type (i + 1)} + \cdots + 1\text{Platoon Planes type(i + n − 1)}$$

2) **Platoon Probability:**

$$P_{platoon(i)} = \frac{Z_i}{\sum_{i=1}^{n} Z_i} \; where \; \{Z_i = \; Platoons\ of\ aircraft\ i\ per\ cycle$$

3) **Headway Matrix:**

Trailing Aircraft (j)	**Leading Aircraft (i)**					**Probabilities (P_j)**
		A	**B**	**C**	**D**	
	A	h_{AA}	h_{BA}	h_{CA}	h_{DA}	$P_{platoonA}$
	B	h_{AB}	h_{BB}	h_{CB}	h_{DB}	$P_{platoonB}$
	C	h_{AC}	h_{BC}	h_{CC}	h_{DC}	$P_{platoonC}$
	D	h_{AD}	h_{BD}	h_{CD}	h_{DD}	$P_{platoonD}$
Probabilities (P_i)		$P_{platoon\ A}$	$P_{platoon\ B}$	$P_{platoon\ C}$	$P_{platoon\ D}$	

Table 8 Headway Matrix for Grouping Method

4) **Average headway between arrivals within the cycle:**

$$h_{cycle} = \frac{D_A + D_B + D_C + D_D + \sum Z_i \cdot D_{platoon\ shift}}{\#\ of\ Planes\ per\ Cycle}$$

$where\ \{\sum Zi = Total\ number\ of\ platoons\ shifts\ within\ a\ cycle.$

We compute the different headways which are in equation above as follows:

- $D_{urationplatoon\ A} = (Q_A - 1) \cdot (h_{aa})$
- $D_{platoon\ B} = (Q_B - 1) \cdot (h_{bb})$
- $D_{platoon\ C} = (Q_C - 1) \cdot (h_{cc})$
- $D_{platoon\ D} = (Q_D - 1) \cdot (h_{dd})$

$$where\ \{Qi = Number\ of\ planes\ within\ platoon\ i$$

- $D_{platoon\ shift} = \sum_{i=1}^{n} \sum_{j=1}^{n} P_{platoon\ i} \cdot h_{ij} \cdot P_{platoon\ j}\ [\frac{Secs}{Platoon-shift}]$

5) Capacity for the grouping method:

$$C = \frac{1}{h_{cycle}} \cdot \frac{3600\ sec}{1\ hour} = [\frac{Arrivals}{hour}]$$

Take-Offs Between Landings Formulation

The ultimate goal of this paper is to optimize the runway capacity so the airports can hold as many operations/hour as possible. Therefore, it is really interesting to study the viability of integrating Take offs in the gap between consecutive landings. In this case the runway will be running both operations (take-offs & landings) at the same time and it would be known as a mixed operations runway. For this to be possible, it is necessary to meet the requirements explained above for Departures following landings (2 NM is the minimum required distance for the following arrivals).

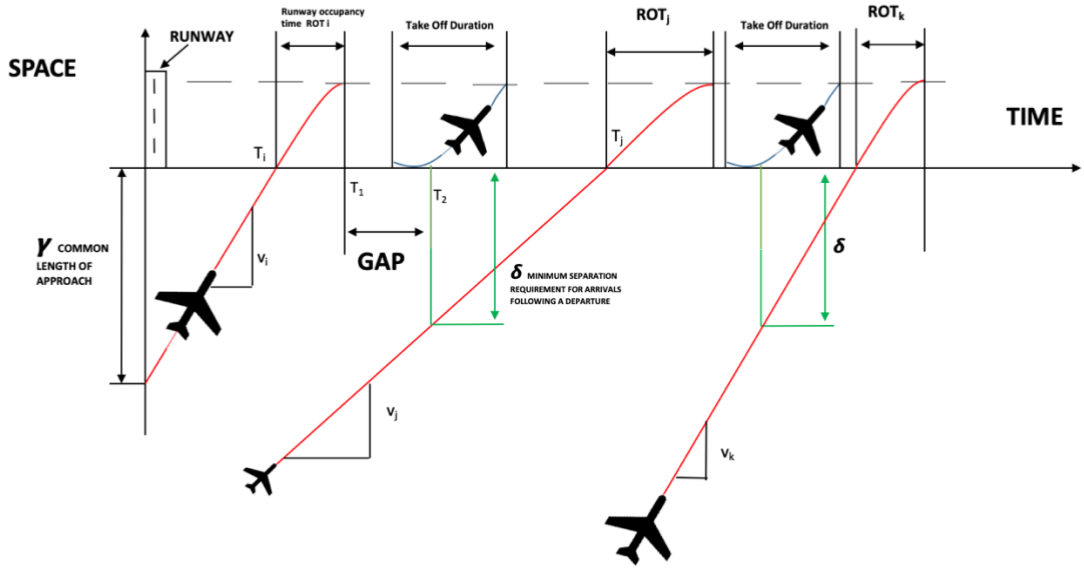


Figure 5 Takeoffs between landings Time-Space Diagrams

As Figure 5 shows, there is room for a plane to take-off to when:

$$T2 - T1 > 0;$$

$$T1 = Ti + ROT_i;$$

$$T2 = Tj - \frac{\delta}{V_j};$$

Where:

$$\begin{cases} T1 = Time\ when\ the\ precedent\ arrival\ exits\ the\ runway \\ T2 = Time\ when\ the\ departure\ begins\ its\ takeoff\ run \\ taking\ into\ accoun\ the\ safety\ margin\ for\ the\ upcoming\ arrival \end{cases}$$

- **Take-Offs Between Landings Optimization**

As stated above, there must exist a gap between two consecutive landings in order to insert a take-off between them. However, there are some border cases where the gap needs only a few more seconds in order to allow the take-off to take place. In this light, sometimes it is more beneficial for the airfield capacity to delay the incoming arrival those seconds and let the ATM use the runway, because this would mean an increase in the number of operations the airport could perform with an insignificant or very low, time cost. The formulation for this analysis would be the following:

VARIABLE	DESCRIPTION	UNITS
h_{CYCLE}	Headway for the grouping method	Secs
T	Time necessary to perform a take-off	Secs
A_{CYCLE}	Airfield Capacity for the grouping method	Operations/hour
q	Number of Cycles	Cycles per hour
N	Number of takeoffs that could be performed within a cycle	Operations/cycle

Table 9 Variables for Take-Offs Optimization

As we know from the formulation of previous sections, the airfield capacity is computed as the inverse of the headway. Therefore, a delay should be applied to the upcoming arrival when the following equation is met:

$$\frac{1}{h_{cycle} + T} \cdot \frac{3600\ secs}{1\ hour} + q[Cycles] \cdot N \left[\frac{Operations}{Cycle}\right] > A_{CYCLE}$$

Therefore, an analysis of these possible situations will be developed with the results obtained for the gaps in both scenarios.

➢ **Delay for Mixed Arrivals Formulation**

A simple runway system can be described by mathematical models or formulas of queueing theory. Arrivals can be satisfactorily described by the Poisson probability distribution. Queuing theory addresses congestion and its causes, and explores the relationships between demand on a service system and congestion in the system manifested by delays suffered by the system users. However, this equations serve us to understand the delay-capacity relationships, they may not provide accurate estimates of average delay, except for simple situations. Assuming Poisson arrivals and constant service times, the Pollaczek-Khinchin formula was derived for average landing delay (Norman J. Ashford, 2011):

$$W = \frac{\rho}{2 \cdot \mu(1-\rho)} = \frac{\rho(1 + Cb^2)}{2\mu(1-\rho)}$$

In order to know what information is needed to compute the average delay for the mixed/random arrivals method, the following variables are defined:

Variable	Description	Units
W	Average Delay	Hours per Arrival
ρ	Load factor	Dimensionless
μ	Mean Runway service time	Seconds per operation
λ	Arrival Rate (Capacity)	Arrivals/Hour
σ	Standard deviation of Mean service time	Seconds per operation
Cb	Coefficient of Variation	Dimensionless
ROTi	Runway occupancy time for Aircraft Class i	Seconds

Table 10 Variables for Average Delay (Pollaczek-Khinchin formula)

- **Mean Runway Service Time & Standard Deviation of Mean Service Time:**

$$\mu = \sum_{i=A}^{N} \frac{ROT_i}{N} \text{ [Seconds/operation] ;} \quad \sigma = \sqrt{\frac{\sum_{i=A}^{N}(ROT_i - \mu)^2}{N}}$$

- **Coefficient of Variation**

$$\text{Cb}=\frac{\sigma}{\mu}$$

- **Load Factor:**

$$\rho_{mixed} = \frac{\lambda\text{mixed}}{\mu} = \frac{\lambda\text{mixed} \cdot \frac{Arrivals}{Hour}}{\frac{1}{\mu \cdot \frac{Seconds}{Arrival}} \cdot \frac{3600secs}{Hour}}$$

$$\rho_{cycle} = \frac{\lambda\text{cycle}}{\mu} = \frac{\lambda\text{cycle} \cdot \frac{Arrivals}{Hour}}{\frac{1}{\mu \cdot \frac{Seconds}{Arrival}} \cdot \frac{3600secs}{Hour}}$$

- **Average Delay per Operation:**

$$W_{Mixed} = \frac{\rho mixed(1+Cb^2)}{2\mu(1-\rho)}$$

$$W_{Cycle} = \frac{\rho cycle(1 + Cb^2)}{2\mu(1-\rho)}$$

➢ **Delay for the Grouping Method**

For the grouping method delay analysis, the variables would be:

Variable	Description	Units
Di	Duration of platoon i per cycle	Seconds
T	Duration of the cycle	Seconds
Ai	Aircraft mix of aircraft type i	Dimensionless
$D_{\text{platoon shift}}$	Average time duration for platoon shifts	Seconds
N	Planes per Cycle	Operations
W	Average Delay	Seconds Per Operation

Table 11Variables Average Delay for the Grouping Method

To estimate this average delay, we will assume a total waiting time of half of the duration of its platoon in the case the plane arrives at the same time its platoon has obtained permission to begin landing. Otherwise, if the plane arrives when a different group is landing, it will have to wait the duration of all the others platoons plus half of its own. This a very simple and conservative way of calculating the average delay that will give us a reasonable approach and comparison to the mixed one. Therefore, the formulation for this first approach would be the following:

- **Platoon probability between each cycle:**

$$\text{Pi} = \frac{Di}{\sum_i^n Di} = \frac{Di}{T}$$

- **Average Delay for two Groups (Small [Class A] & Large[Class C])**

$$W = A_{small} \cdot \left(P_{small} \cdot \frac{1}{2} \cdot D_{small} + P_{large} \cdot \left(D_{large} + h_{shift} + \frac{1}{2} D_{small} \right) \right) + A_{large} \cdot (P_{large}$$

$$\cdot \frac{1}{2} \cdot D_{large} + P_{small} \cdot \left(D_{small} + h_{shift} + \frac{1}{2} D_{large} \right)$$

$$Dshift = A_{small} \cdot h_{small-large} + A_{large} \cdot h_{large-small}$$

- **Average delay for all aircrafts groups**

The shift headway will be computed as mean of the all headway shifts as we will assume that the platoon order inside a cycle is not known. Therefore, the shift headway would be the following:

$$D_{shift} = \sum_{i=A}^{D} A_i \cdot \sum_{j=A}^{D} \frac{h_{ij}}{N-1} \qquad for\ all \qquad i \neq j$$

Cycle Order: Platoon A – Platoon B – Platoon C – Platoon D

Average delay for Aircraft type A:

$$W_A = A_A \cdot (P_A \cdot \frac{1}{2} \cdot D_A + P_B \cdot \left(D_B + D_C + D_D + 3 \cdot h_{shift} + \frac{1}{2} \cdot D_A\right) + P_C \cdot \left(D_C + D_D + 2 \cdot h_{shift} + \frac{1}{2} \cdot D_A\right) + P_D \cdot \left(D_D + h_{shift} + \frac{1}{2} \cdot D_A\right))$$

Average delay for Aircraft type B:

$$W_B = A_B \cdot (P_B \cdot \frac{1}{2} \cdot D_B + P_C \cdot \left(D_C + D_D + D_A + 3 \cdot h_{shift} + \frac{1}{2} \cdot D_B\right) + P_D \cdot \left(D_D + D_A + 2 \cdot h_{shift} + \frac{1}{2} \cdot D_B\right) + P_A \cdot (D_A + h_{shift} + \frac{1}{2} \cdot D_B)$$

Average delay for Aircraft type C:

$$W_C = A_C \cdot (P_C \cdot \frac{1}{2} \cdot D_C + P_D \cdot \left(D_D + D_A + D_B + 3 \cdot h_{shift} + \frac{1}{2} \cdot D_C\right) + P_A \cdot \left(D_A + D_B + 2 \cdot h_{shift} + \frac{1}{2} \cdot D_C\right) + P_B \cdot (D_B + h_{shift} + \frac{1}{2} \cdot D_C)$$

Average delay for Aircraft type D:

$$W_D = A_D \cdot (P_D \cdot \frac{1}{2} \cdot D_D + P_A \cdot \left(D_A + D_B + D_C + 3 \cdot h_{shift} + \frac{1}{2} \cdot D_D\right) + P_B \cdot \left(D_B + D_C + 2 \cdot h_{shift} + \frac{1}{2} \cdot D_D\right) + P_C \cdot (D_C + h_{shift} + \frac{1}{2} \cdot D_D)$$

Average Delay for any plane in the cycle when the grouping method is being used:

$$Wcycle = W_A + W_B + W_C + W_D$$

RESULTS

➢ Basic Case – 1 Runway & 2 Aircraft Types

Ns (Small Planes)	N_L (Large Planes)	P Aircraft Mix Small (A)	P_L Aircraft Mix Large (C)	V_s Velocity of Small	V_L Velocity of Large	γ length of common approach	Platoons per Cycle	Cycle Size (Planes per Cycle)
4	6	40%	60%	91	121	6	2	10

Table 12 Basic Case Parameters

Mixed Method Time-Space Diagram:

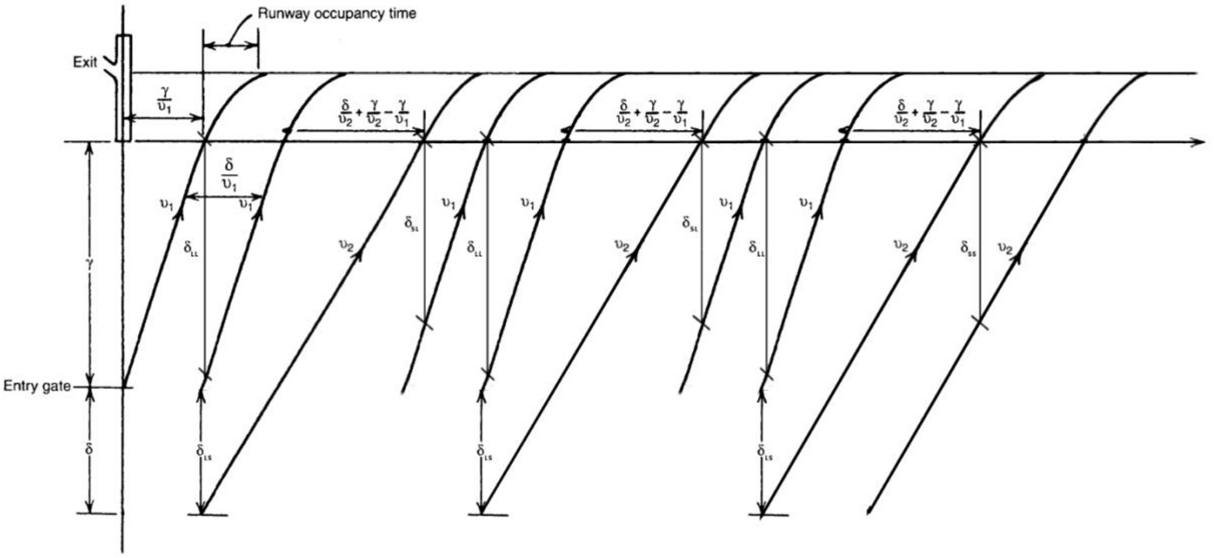


Figure 6 Time Space Diagram for Random Order Arrivals

Grouping Method Time-Space Diagram:

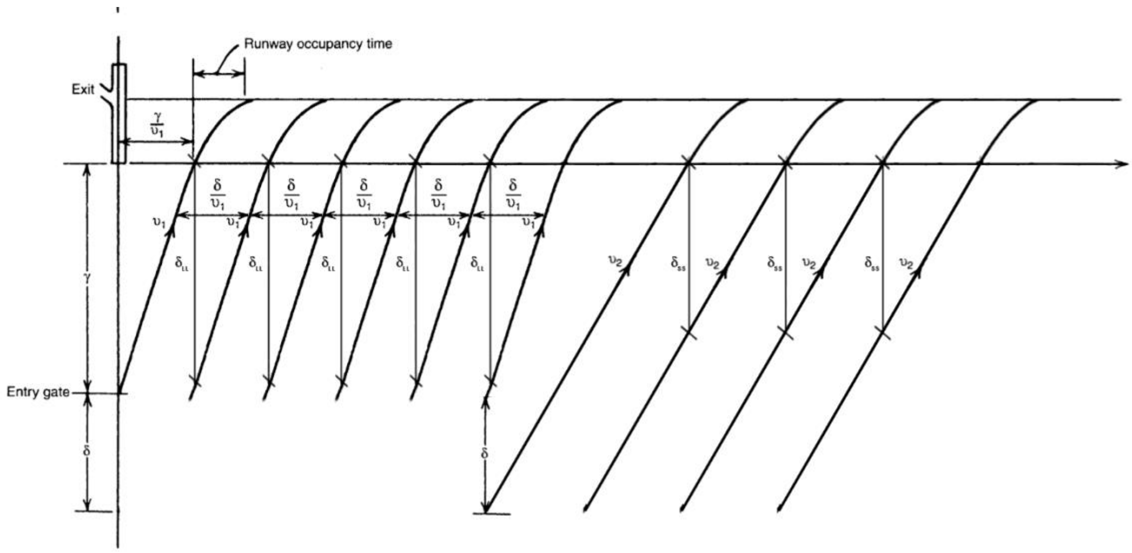


Figure 7 Time Space Diagram for the grouping method Arrivals

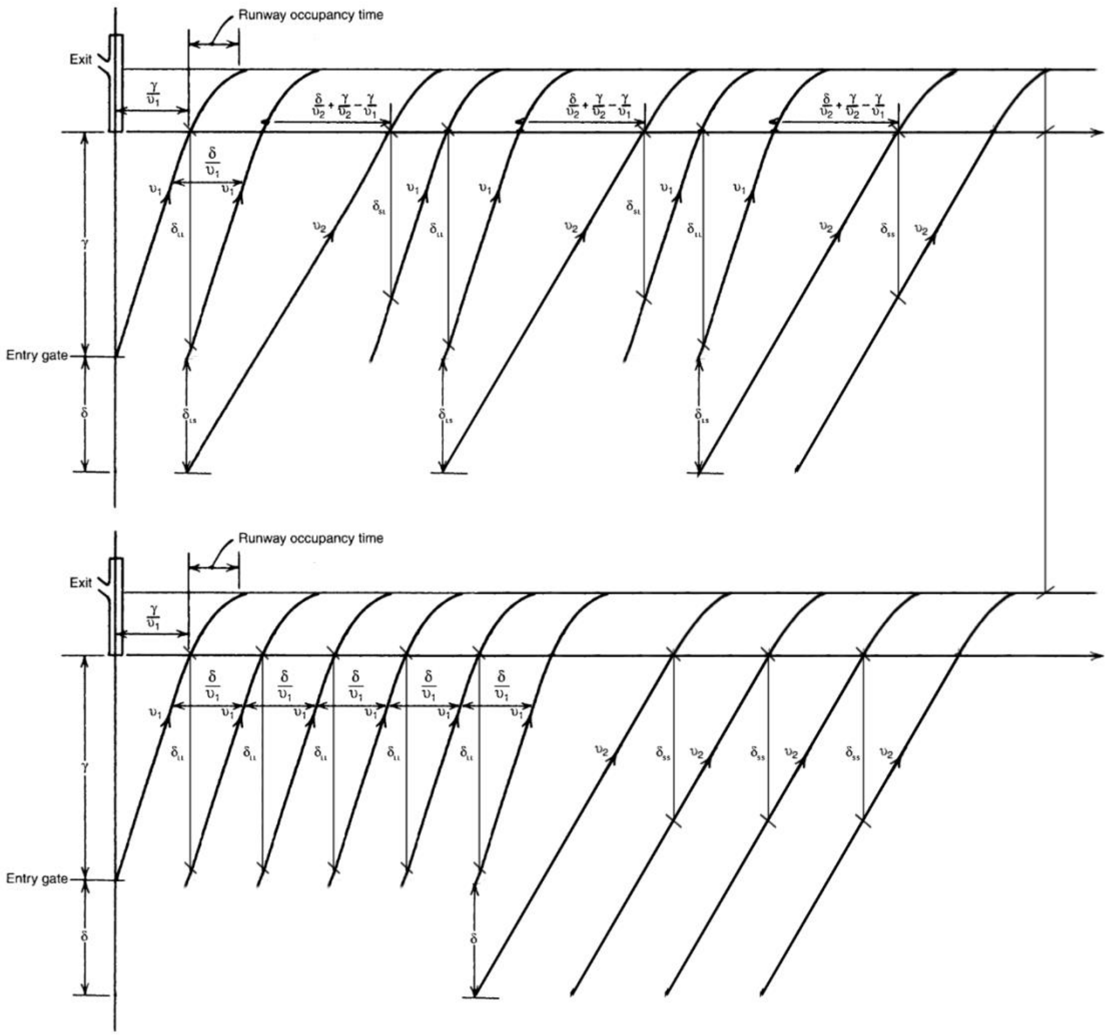


Figure 8 Time Space Diagrams Comparison

<u>Headway Matrix for Mixed Arrivals:</u>

Trailing Aircraft (j)	Leading Aircraft (i)			Probabilities (P_j)
		Small (A)	**Large (C)**	
	Small (A)	98.91	217.092	0.4
	Large (C)	74.38	89.25	0.6
Probabilities (P_i)		0.4	0.6	

Table 13 Basic Case Headway Matrix Mixed Arrivals

Headway Matrix for Grouped Arrivals:

Trailing Aircraft (j)	Leading Aircraft (i)			Platoon Probability
		Small (Planes type A)	Large (Planes type C)	
	Small (A)	98.91	217.092	0.5
	Large (C)	74.38	89.25	0.5
Platoon Probability		0.5	0.5	

Table 14 Basic Case Headway Matrix Grouping Method

Once the formulation explained above is applied for this specific problem we obtain the following result, that shows a clear increase of the airfield capacity when the hypothetical airport operates with a grouping-method.

METHOD	AVG HEADWAY	CAPACITY
MIXED ARRIVALS	117.91 secs	$30.5\ \frac{operations}{hour}$
GROUPED ARRIVALS	88.87 secs	$40.51\,\frac{operations}{hour}$

Table 15 Summary Results Basic Case

Furthermore, a sensitivity analysis was carried out comparing how much the capacity would change when the airport expects aircraft mixes different from (40% A & 60 % C). The chart below clearly reveals an increase of the capacity when the number of planes of type C is greater than the number of A planes.

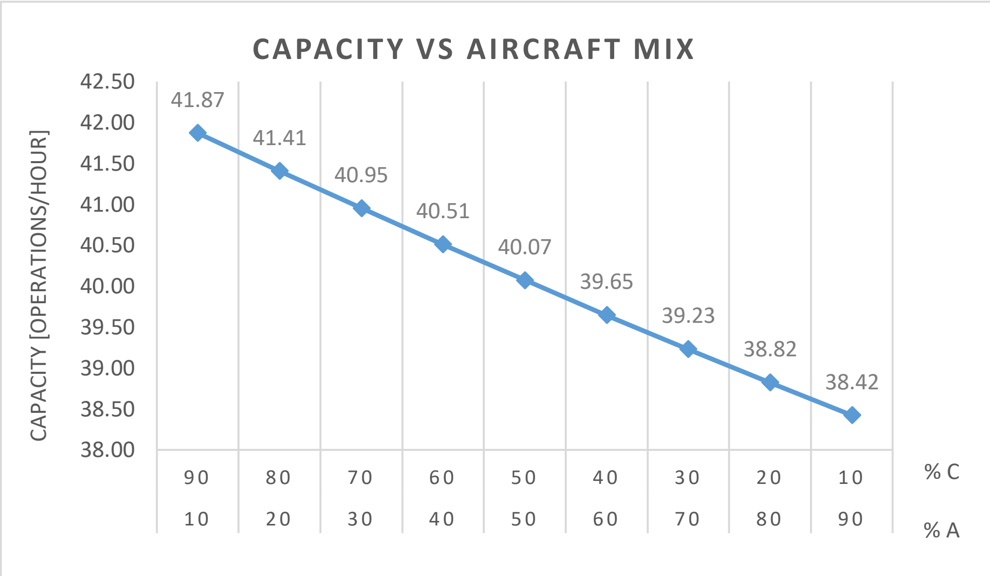


Figure 9 Capacity versus Aircraft Mix Comparison

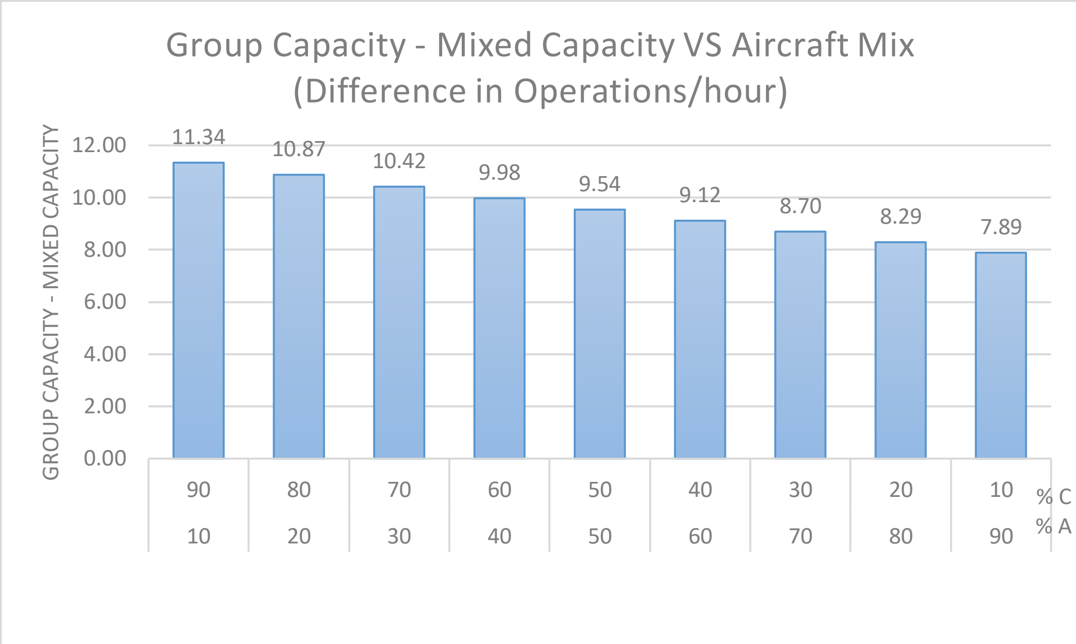


Figure 10 Difference in Airfield Capacity between Grouping Method and Random order for different mixes

- **2nd Scenario 1 Runway & 4 Aircraft Types**

The second scenario we will be studying is the same one-runway airport but in this case any type of aircraft could be asking permission for landing. Therefore, we will have one runway and four aircraft types. The data used to simulate this scenario is the following:

AIRCRAFT TYPE	APPROACHING SPEED	AIRCRAFT MIX	PLANES PER PLATOON
A	90 KNOTS	20%	2
B	110 KNOTS	40%	4
C	130 KNOTS	20%	2
D	150 KNOTS	20%	2
TOTAL PLANES PER CYCLE			10

Table 16 2nd Scenario Parameters

The results obtained for this simulation still reveal an improvement in airfield capacity when the airport is using a grouping method. This means that there could be room for improvement in this area although we are making important assumptions.

METHOD	AVG HEADWAY	CAPACITY
MIXED ARRIVALS	119.85 secs	$30.04\ \frac{operations}{hour}$
GROUPED ARRIVALS	104,5 secs	$34{,}53\ \frac{operations}{hour}$

Table 17 2nd Scenario Results

The above calculations accounts for a cycle size of 10 planes. It is interesting to analyze the effects the cycle size would have on the final airfield capacity. We can see this in Fig. 9:

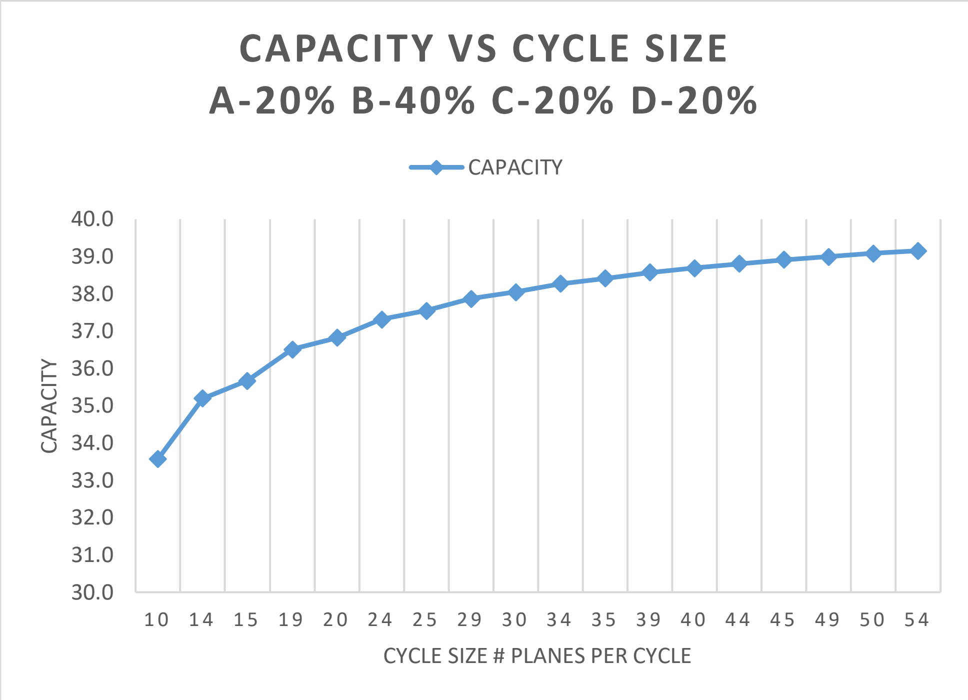


Figure 11 Capacity versus Cycle Size for a determined Aircraft Mix

From Fig. 11 we can conclude that the cycle size does affect the airfield capacity but less than switching from the FCFS method to the grouping method. As we can see, the capacity difference between the smallest cycle size (10 planes) with the biggest cycle size (54 planes) is only 1.8 Arrivals per hour more.

In addition, it is interesting to investigate how much the capacity would change when airports experience different aircraft mixes than the ones used for the mathematical calculation. Therefore, for the given typical speeds of each aircraft type the fluctuation on capacity due to the aircraft mix is the following:

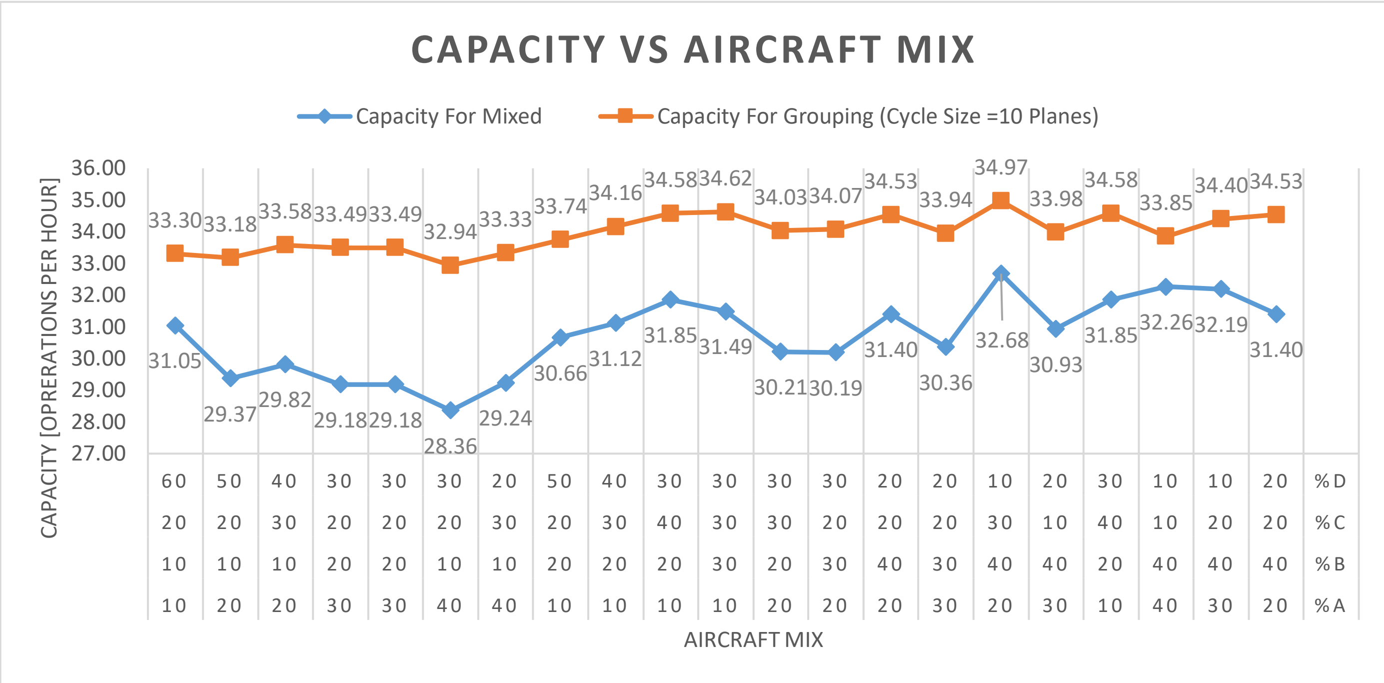


Figure 12 Capacity versus Aircraft Mix with Four Aircraft Types

- **<u>Gaps for the Basic Case</u>**

Velocity of Small	Velocity of Large	Safety Margin δ (Specified by the FAA)	ROTs for Small Arrivals	ROT_L for Large Arrivals	H_{ss} Headway for small-large	H_{ll} Headway for large-large	H_{LS} Headway for large-small	H_{SL} Headway Small-Large
91 Knots	121 Knots	2 NM	40 secs	45 secs	98.9 secs	89.26 sec	217.09 sec	74.38secs

Table 18 Parameters Gaps for the Basic Case

1. **<u>TAKEOFF BETWEEN SMALL-SMALL ARRIVAL:</u>**

$$T1 = Ti + ROTs = 0 + 40 = 40secs$$

$$T2 = Hss - \frac{\delta}{Vs} = 98.9 - \frac{2}{91} \cdot \frac{3600secs}{1Hour} = 19.8\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 19.8 - 40 = -20.2secs$$

$$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$$

2. **<u>TAKEOFF BETWEEN SMALL-LARGE ARRIVAL:</u>**

$$T1 = Ti + ROTs = 0 + 40 = 40secs$$

$$T2 = Hsl - \frac{\delta}{Vl} = 74.38 - \frac{2}{121} \cdot \frac{3600secs}{1Hour} = 14.876\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 14.876 - 40 = -25.12secs$$

$$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$$

3. **TAKEOFF BETWEEN LARGE-LARGE ARRIVAL:**

$$T1 = Ti + ROTl = 0 + 45 = 45secs$$

$$T2 = Hll - \frac{\delta}{Vl} = 89.26 - \frac{2}{121} \cdot \frac{3600secs}{1Hour} = 29.76\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 29.76 - 45 = -10.24secs$$

$$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$$

4. **TAKEOFF BETWEEN LARGE-SMALL ARRIVAL:**

$$T1 = Ti + ROTl = 0 + 45 = 45secs$$

$$T2 = Hls - \frac{\delta}{Vs} = 217.09 - \frac{2}{91} \cdot \frac{3600secs}{1Hour} = 137.97secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 137.97 - 45 = 92.97secs$$

$$\rightarrow TAKE\ OFF\ IS\ POSSIBLE$$

➢ **Gaps for 1 Runway & 4 types of Aircraft:**

The formulation would be the same as the above calculations with the difference that in these case we have 16 possible Gaps:

Aircraft Type	Velocity (KNOTS)	ROTi	Safety Margin δ
A	91	40	2
B	110	43	2
C	130	48	2
D	150	53	2

LEADING AIRCRAFT					
	HEADWAY MATRIX	**A**	**B**	**C**	**D**
TRAILING AIRCRAFT	**A**	98,90	139,90	229,45	310,95
	B	81,82	81,82	161,12	232,36
	C	69,23	69,23	83,08	160,62
	D	60,00	60,00	72,00	96,00

Table 19 Parameters & Headway Matrix for 2nd Scenario Gaps Analysis

1. **TAKEOFF BETWEEN A - A ARRIVAL:**

$$T1 = Ti + ROTa = 0 + 40 = 40secs$$

$$T2 = H_{AA} - \frac{\delta}{Va} = 98.9 - \frac{2}{91} \cdot \frac{3600secs}{1Hour} = 19.8\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 19.8 - 40 = -20.2secs$$

$$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$$

2. **TAKEOFF BETWEEN A – B ARRIVAL:**

$$T1 = Ti + ROTa = 0 + 40 = 40secs$$

$$T2 = H_{AB} - \frac{\delta}{Vb} = 81.82 - \frac{2}{110} \cdot \frac{3600secs}{1Hour} = 16.36 \text{ secs}$$

$Gap\ Exists\ if\ T2 - T1 > 0$ $\qquad Gap = T2 - T1 = 16.36 - 40 = -23.64secs$

$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$

3. **TAKEOFF BETWEEN A - C ARRIVAL:**

$$T1 = Ti + ROTa = 0 + 40 = 40secs$$

$$T2 = H_{AC} - \frac{\delta}{Vc} = 69.23 - \frac{2}{130} \cdot \frac{3600secs}{1Hour} = 13.85\ secs$$

$Gap\ Exists\ if\ T2 - T1 > 0$ $\qquad Gap = T2 - T1 = 13.85 - 40 = -26.15secs$

$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$

4. **TAKEOFF BETWEEN A - D ARRIVAL:**

$$T1 = Ti + ROTa = 0 + 40 = 40secs$$

$$T2 = H_{AC} - \frac{\delta}{Vd} = 60 - \frac{2}{150} \cdot \frac{3600secs}{1Hour} = 12\ secs$$

$Gap\ Exists\ if\ T2 - T1 > 0$ $\qquad Gap = T2 - T1 = 12 - 40 = -28\ secs$

$\rightarrow NO\ TAKE\ OFF\ \ IS\ POSSIBLE$

5. **TAKEOFF BETWEEN B - B ARRIVAL:**

$$T1 = Ti + ROTb = 0 + 43 = 43secs$$

$$T2 = H_{BB} - \frac{\delta}{Vb} = 81.82 - \frac{2}{110} \cdot \frac{3600secs}{1Hour} = 16.36\ secs$$

$Gap\ Exists\ if\ T2 - T1 > 0$ $\qquad Gap = T2 - T1 = 16.36 - 43 = -26.63secs$

$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$

6. **TAKEOFF BETWEEN B - A ARRIVAL:**

$$T1 = Ti + ROTb = 0 + 43 = 43secs$$

$$T2 = H_{BA} - \frac{\delta}{Va} = 139.9 - \frac{2}{91} \cdot \frac{3600secs}{1Hour} = 60.78\ secs$$

$Gap\ Exists\ if\ T2 - T1 > 0$ $\qquad Gap = T2 - T1 = 60.78 - 43 = 17.78secs$

$\rightarrow\ TAKE\ OFF\ IS\ POSSIBLE$

7. **TAKEOFF BETWEEN B - C ARRIVAL:**

$$T1 = Ti + ROTb = 0 + 43 = 43secs$$

$$T2 = H_{BC} - \frac{\delta}{Vc} = 69.23 - \frac{2}{130} \cdot \frac{3600secs}{1Hour} = 13.85\ secs$$

$Gap\ Exists\ if\ T2 - T1 > 0$ $\qquad Gap = T2 - T1 = 13.85 - 43 = -26.15secs$

$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$

8. **TAKEOFF BETWEEN B - D ARRIVAL:**

$$T1 = Ti + ROTb = 0 + 43 = 43secs$$

$$T2 = H_{AC} - \frac{\delta}{Vd} = 60 - \frac{2}{150} \cdot \frac{3600secs}{1Hour} = 12\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 12 - 43 = -31secs$$

$$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$$

9. TAKEOFF BETWEEN C - A ARRIVAL:

$$T1 = Ti + ROTc = 0 + 48 = 48secs$$

$$T2 = H_{CA} - \frac{\delta}{Va} = 229.45 - \frac{2}{91} \cdot \frac{3600secs}{1Hour} = 150.33\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 150.33 - 48 = 102.33\ secs$$

$$\rightarrow TAKE\ OFF\ IS\ POSSIBLE$$

10. TAKEOFF BETWEEN C - B ARRIVAL:

$$T1 = Ti + ROTc = 0 + 48 = 48secs$$

$$T2 = H_{CB} - \frac{\delta}{Vb} = 161.12 - \frac{2}{110} \cdot \frac{3600secs}{1Hour} = 95.66\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 95.66 - 48 = 47.66\ secs$$

$$\rightarrow TAKE\ OFF\ IS\ POSSIBLE$$

11. TAKEOFF BETWEEN C - C ARRIVAL:

$$T1 = Ti + ROTc = 0 + 48 = 48secs$$

$$T2 = H_{CC} - \frac{\delta}{Vc} = 83.08 - \frac{2}{130} \cdot \frac{3600secs}{1Hour} = 27.69\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 27.69 - 48 = -20.31\ secs$$

$$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$$

12. TAKEOFF BETWEEN C – D ARRIVAL:

$$T1 = Ti + ROTc = 0 + 48 = 48secs$$

$$T2 = H_{CD} - \frac{\delta}{Vd} = 72 - \frac{2}{150} \cdot \frac{3600secs}{1Hour} = 24\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 24 - 48 = -24\ secs$$

$$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$$

13. TAKEOFF BETWEEN D - A ARRIVAL:

$$T1 = Ti + ROTd = 0 + 53 = 48secs$$

$$T2 = H_{DA} - \frac{\delta}{Vd} = 310.95 - \frac{2}{91} \cdot \frac{3600secs}{1Hour} = 231.83\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 231.83 - 53 = 178.83\ secs$$

$$\rightarrow TAKE\ OFF\ IS\ POSSIBLE$$

14. TAKEOFF BETWEEN D - B ARRIVAL:

$$T1 = Ti + ROTd = 0 + 53 = 48secs$$

$$T2 = H_{DB} - \frac{\delta}{Vb} = 232.36 - \frac{2}{110} \cdot \frac{3600secs}{1Hour} = 166.905\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 166.905 - 53 = 113.905\ secs$$

$$\rightarrow TAKE\ OFF\ IS\ POSSIBLE$$

15. <u>TAKEOFF BETWEEN D - C ARRIVAL:</u>

$$T1 = Ti + ROTd = 0 + 53 = 48secs$$

$$T2 = H_{DC} - \frac{\delta}{Vc} = 160.62 - \frac{2}{130} \cdot \frac{3600secs}{1Hour} = 105.235secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 105.235 - 53 = 52.23\ secs$$

$$\rightarrow TAKE\ OFF\ IS\ POSSIBLE$$

16. <u>TAKEOFF BETWEEN D – D ARRIVAL:</u>

$$T1 = Ti + ROTd = 0 + 53 = 48secs$$

$$T2 = H_{DD} - \frac{\delta}{Vd} = 96 - \frac{2}{150} \cdot \frac{3600secs}{1Hour} = 48\ secs$$

$$Gap\ Exists\ if\ T2 - T1 > 0 \qquad Gap = T2 - T1 = 48 - 53 = -3\ secs$$

$$\rightarrow NO\ TAKE\ OFF\ IS\ POSSIBLE$$

After the results obtained, we could say that every time a smaller aircraft is following a larger arrival there is enough gap for takeoffs to take place. The total impact this will have to the airfield capacity would depend on the number of shifts between larger & smaller arrivals within an hour but it could definitely result in a major increase in the overall airport capacity. Once again, we made some error-free departures and perfect timing for ATM & pilots assumptions for this gaps analysis. The real gaps will be slightly different as they would take into account taxiways times, takeoff queues & air traffic controller workload. However, it is a really interesting field of study looking forward to increase capacity.

➢ <u>Gaps Optimization for 1 Runway & 2 Aircraft Types:</u>

For the first Scenario, we obtained the following results that we would need to study if the gap distribution could give us a better result for the airfield capacity:

Average Headway Mixed	117,91 secs
Average Headway Cycle	88,87 secs
Cycles per hour	4,05
Airfield Capacity for the grouping method	40,5

Table 20 Gaps Optimization Basic Scenario

The cases where we could not perform a takeoff according to the first results of the gap section were:

- **<u>TAKEOFF BETWEEN SMALL-SMALL ARRIVAL:</u>**

Minimum time needed to perform a takeoff T = 21 secs (from previous section).

Number of possible gaps per cycle: 3 (Platoon of 4 small planes).

$$\frac{1}{h_{cycle}+T}\cdot\frac{3600\ secs}{1\ hour}+q[Cycles]\cdot N\left[\frac{Operations}{Cycle}\right]>A_{CYCLE}$$

$$\frac{1}{88{,}87+21}\cdot\frac{3600\ secs}{1\ hour}+4{,}05\cdot 3=44.16\ Operations\ per\ hour$$

As the overall capacity increases, it would be a reasonable decision to apply a delay for the upcoming arrival.

- **<u>TAKEOFF BETWEEN SMALL-LARGE ARRIVAL:</u>**

Minimum time needed to perform a takeoff T = 25 secs (from previous section).

Number of possible gaps per cycle: 1 (Only 1 shift of platoons within a cycle).

$$\frac{1}{h_{cycle}+T}\cdot\frac{3600\ secs}{1\ hour}+q[Cycles]\cdot N\left[\frac{Operations}{Cycle}\right]>A_{CYCLE}$$

$$\frac{1}{88{,}87+25}\cdot\frac{3600\ secs}{1\ hour}+4{,}05\cdot 1=35.61\ Operations\ per\ hour$$

As the overall capacity is lower than the previous one, it would not be a reasonable decision to apply a delay for the upcoming arrival.

- **<u>TAKEOFF BETWEEN LARGE-LARGE ARRIVAL:</u>**

Minimum time needed to perform a takeoff T = 10 secs (from previous section).

Number of possible gaps per cycle: 5 (5 possible gaps within a cycle 6 large planes/cycle).

$$\frac{1}{h_{cycle}+T}\cdot\frac{3600\ secs}{1\ hour}+q[Cycles]\cdot N\left[\frac{Operations}{Cycle}\right]>A_{CYCLE}$$

$$\frac{1}{88{,}87+10}\cdot\frac{3600\ secs}{1\ hour}+4{,}05\cdot 5=56{,}29\ Operations\ per\ hour$$

As the overall capacity increases, it would be a reasonable decision to apply a delay for the upcoming arrival.

- GAPS optimization for 1 Runway & 4 Aircraft Types:

Average Headway Mixed	119,85 secs
Average Headway Cycle	93,51 secs
Cycles per hour	3,85 cycle
Airfield Capacity for the grouping method	38,5 operations per hour

Table 21 Gaps Optimization 2nd Scenario

1. TAKEOFF BETWEEN A - A ARRIVAL:

Minimum time needed to perform a takeoff T = 20 secs (from previous section).

Number of possible gaps per cycle: 1 (Only 1 possible gap between A-A arrivals).

$$\frac{1}{h_{cycle}+T}\cdot\frac{3600\ secs}{1\ hour}+q[Cycles]\cdot N\left[\frac{Operations}{Cycle}\right]>A_{CYCLE}$$

$$\frac{1}{93{,}51+20}\cdot\frac{3600\ secs}{1\ hour}+3{,}85\cdot 1=35.56\ Operations\ per\ hour$$

As the overall capacity is lower than the previous one, it would not be a reasonable decision to apply a delay for the upcoming arrival.

2. TAKEOFF BETWEEN A – B ARRIVAL:

Minimum time needed to perform a takeoff T = 23.56 secs (from previous section).

Number of possible gaps per cycle: 1 (Only 1 shift of platoons within a cycle).

$$\frac{1}{h_{cycle}+T}\cdot\frac{3600\ secs}{1\ hour}+q[Cycles]\cdot N\left[\frac{Operations}{Cycle}\right]>A_{CYCLE}$$

$$\frac{1}{93{,}51+23.56}\cdot\frac{3600\ secs}{1\ hour}+3{,}85\cdot 1=34.6\ Operations\ per\ hour$$

As the overall capacity is lower than the previous one, it would not be a reasonable decision to apply a delay for the upcoming arrival.

3. TAKEOFF BETWEEN B - B ARRIVAL:

Minimum time needed to perform a takeoff T = 26.63 secs (from previous section).

Number of possible gaps per cycle: 3 (3 possible gaps for B-B within a cycle).

$$\frac{1}{h_{cycle}+T}\cdot\frac{3600\ secs}{1\ hour}+q[Cycles]\cdot N\left[\frac{Operations}{Cycle}\right]>A_{CYCLE}$$

$$\frac{1}{93{,}51 + 26.63} \cdot \frac{3600\ secs}{1\ hour} + 3{,}85 \cdot 3 = \ 41.51\ Operations\ per\ hour$$

As the overall capacity increases, it would be reasonable to apply a delay for the upcoming arrival.

4. TAKEOFF BETWEEN B - C ARRIVAL:

Minimum time needed to perform a takeoff T = 27 secs (from previous section).
Number of possible gaps per cycle: 1 (1 possible gaps for B-C within a cycle 1 shift per cycle).

$$\frac{1}{h_{cycle} + T} \cdot \frac{3600\ secs}{1\ hour} + q[Cycles] \cdot N \left[\frac{Operations}{Cycle}\right] > A_{CYCLE}$$

$$\frac{1}{93{,}51 + 27} \cdot \frac{3600\ secs}{1\ hour} + 3{,}85 \cdot 1 = \ 33.723\ Operations\ per\ hour$$

As the overall capacity is lower than the previous one, it would not be a reasonable decision to apply a delay for the upcoming arrival.

5. TAKEOFF BETWEEN C - C ARRIVAL:

Minimum time needed to perform a takeoff T = 20.31 secs (from previous section).
Number of possible gaps per cycle: 1 (1 possible gaps for C-C within a cycle 1 shift per cycle).

$$\frac{1}{h_{cycle} + T} \cdot \frac{3600\ secs}{1\ hour} + q[Cycles] \cdot N \left[\frac{Operations}{Cycle}\right] > A_{CYCLE}$$

$$\frac{1}{93{,}51 + 20.31} \cdot \frac{3600\ secs}{1\ hour} + 3{,}85 \cdot 1 = \ 35.479\ Operations\ per\ hour$$

As the overall capacity is lower than the previous one, it would not be a reasonable decision to apply a delay for the upcoming arrival.

➢ Delay- Using Pollaczek-Khinchin formula

Capacity for Mixed=30.53arrivals/hour **Capacity for Cycle Method**=40.5 Arrivals/hour

- **Mean Runway Service Time & Standard Deviation of Mean Service Time**

$$\mu = \sum_{i=A}^{N} \frac{ROT_i}{N} \text{ [Seconds/operation]}; \qquad \sigma = \sqrt{\frac{\sum_{i=A}^{N}(ROT_i-\mu)^2}{N}}$$

$$\mu = 46.7secs \quad \sigma = \sqrt{\frac{(38-41.5)^2+(45-41.5)^2}{2}} = 2.62\ secs$$

The value of the mean runway service time has been taken from: (Vivek Kumar, 2009)

Coefficient of Variation → Cb=$\frac{\sigma}{\mu} = 0.056$

Arrival Rate → λ_{mixed}=30.53 Arrivals/Hour λ_{Cycle}=34.53 Arrivals per hour

- **Load Factor:**

$$\rho_{mixed} = \frac{\lambda mixed}{\mu} = \frac{30.53 \cdot \frac{Arrivals}{Hour}}{\frac{1}{46.7 \cdot \frac{Seconds}{Arrival}} \cdot \frac{3600secs}{Hour}} = 0.396$$

$$\rho_{cycle} = \frac{\lambda cycle}{\mu} = \frac{40.5 \cdot \frac{Arrivals}{Hour}}{\frac{1}{46.7 \cdot \frac{Seconds}{Arrival}} \cdot \frac{3600secs}{Hour}} = 0.467$$

- **Average Delay per Operation:**

$$W_{Mixed} = \frac{\rho(1+Cb^2)}{2\mu(1-\rho)} = \frac{0.352 \cdot (1+0.084^2)}{2 \cdot \frac{1}{46.7\frac{secs}{operation}} \frac{3600secs}{1Hour} \cdot (1-0.352)} = 0.007015 \frac{Hour}{Operation}$$

$$= 25.35 \frac{secs}{operation}$$

$$W_{Cycle} = \frac{\rho(1+Cb^2)}{2\mu(1-\rho)} = \frac{0.467 \cdot (1+0.084^2)}{2 \cdot \frac{1}{41.5\frac{secs}{operation}} \frac{3600secs}{1Hour} \cdot (1-0.467)} = 0.0118 \frac{Hour}{Operation}$$

$$= 42.79 \frac{secs}{operation}$$

As we can see from the results obtained for the basic case, the average delay will be greater when we apply the grouping method. This could be considered as a disadvantage for the mixed operation because the planes will have to spend more time waiting which means more fuel costs and machine time. Although the example above shows a numerical difference of the average delay, we have developed a sensitivity analysis of the AVG Delay versus Capacity as shown below.

- **Average Delay vs Capacity**:

Fig. 7 shows how the average delay changes as we increase the number of operations per hour that hypothetically an airport could perform. The 5 different colors are 5 possible coefficient of variation. It can be inferred that according to the Pollaczek-Khinchin formula, the average delay would increase exponentially in relation to the capacity.

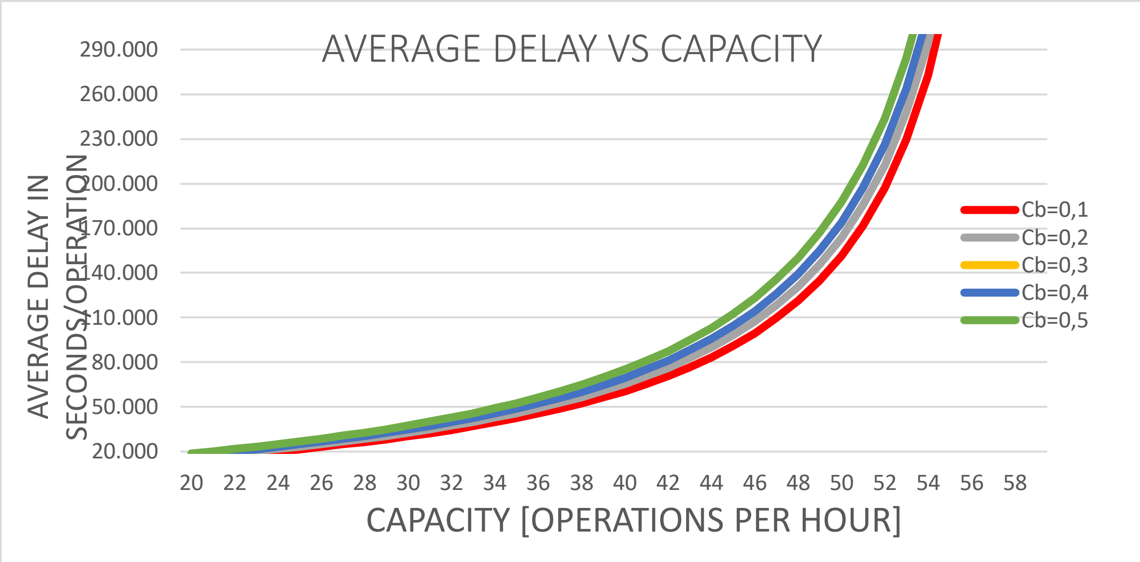
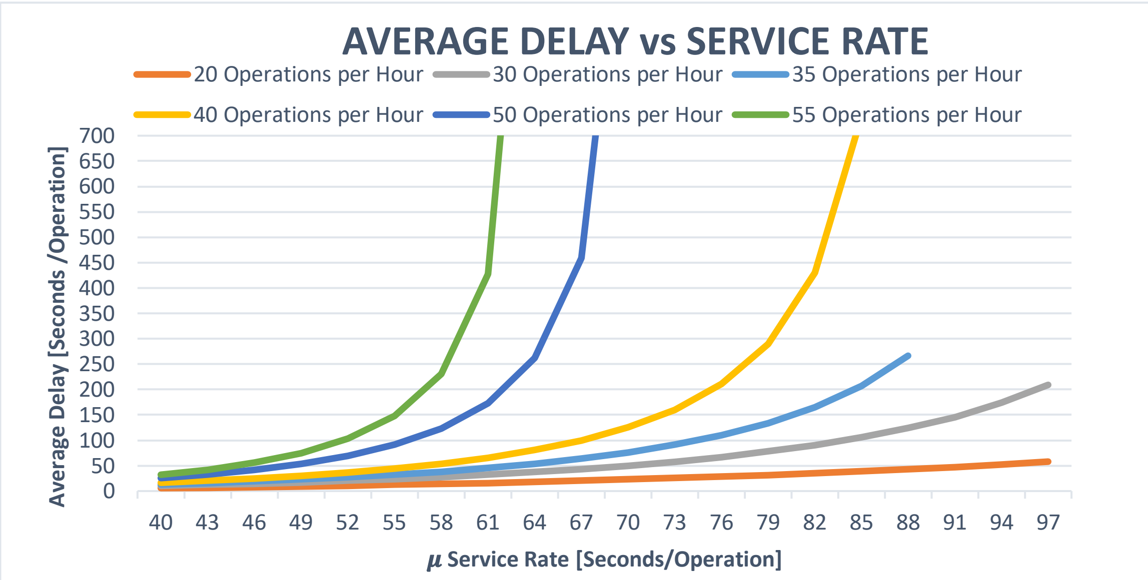


Figure 13 Average Delay versus Capacity for Given Aircraft Mix of (40% A, 60% B)



Here we can see the relation between the average delay per operation and the mean service time of the runway. Fig. 8 shows how the average delay would change for six constant capacity values at variable runway service times. It clearly shows that increasing the mean service time of the runway implies greater average delay.

➢ Average Delay for Grouping Method:

1st Scenario: 2 Aircrafts (A & C) & 1 Runway (Aircraft Mix: A:40% C:60%)

Small(A) Planes per cycle	4 planes
Large (C) Planes per cycle	6 planes
Planes per cycle	10 planes
Duration Small Platoon	296,7 secs
Duration Large Platoon	446,28 secs
Mean Platoon's shift duration	145,74 secs
Probability of Small Platoon	0,42
Probability of Large Platoon	0,58
Average Delay Per Cycle	**441,95 secs**
Average Delay per Operation	**44,195secs**

Table 22 Average Delay Basic Scenario Results

2nd Scenario: All Aircrafts & 1 Runway (Aircraft Mix: A:20% B:40% C:20% D:20%)

In this scenario, we will compare the average delay for a cycle of the same aircraft mix but different cycle size:

Scenario	10 Planes per Cycle	20 Planes per cycle
Duration Platoon Aircraft A	98,9 secs	296,70 secs
Duration Platoon Aircraft B	225 secs	525,00 secs
Duration Platoon Aircraft C	86,40 secs	259,20 secs
Duration Platoon Aircraft D	99,31 secs	297,93 secs
Planes type A per cycle	2 planes	2 planes
Planes type B per cycle	4 planes	4 planes
Planes type C per cycle	2 planes	2 planes
Planes type D per cycle	2 planes	2 planes
Planes per cycle	10 planes	20 planes

Mean Platoon's shift duration	125,60 secs	125,6 secs
Probability of Platoon A	0,22	0,22
Probability of Platoon B	0,35	0,35
Probability of Platoon C	0,21	0,20
Probability of Platoon D	0,22	0,23
Average Delay Per Cycle	**441,95 secs**	**871,57 secs**
Average Delay per Operation	**45,47secs**	**44,72 secs**
Airfield Capacity	**39,6 operations/hour**	**40,51 operations/hour**

Table 23 Average Delay 2nd Scenario Resultts

SENSITIVITY ANALYSIS

In order to obtain more information about the grouping method, the different effects it would have on five aircraft mixes have been evaluated. The five mixes analyzed are:

- 1st Scenario: A:20% B:40% C:20% D:20%
- 2nd Scenario: A:0% B:30% C:30% D:40%
- 3rd Scenario: A:10% B:40% C:50% D:0%
- 4th Scenario: A:30% B:20% C:30% D:20%
- 5th Scenario: A:10% B:20% C:30% D:40%

Firstly, the mixes have been evaluated and compared for an expected cycle size of 10 aircraft as it has been done in the previous cases. After this, an analysis of how the important factors would vary for different cycle sizes has been developed.

1. Average Headway & Capacity

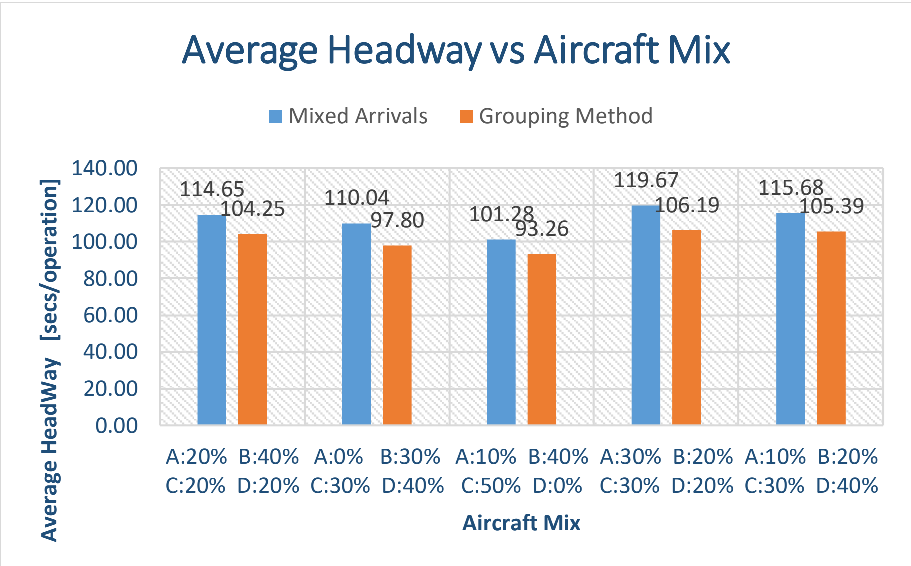


Figure 14 Avg. Headway vs Aircraft Mix

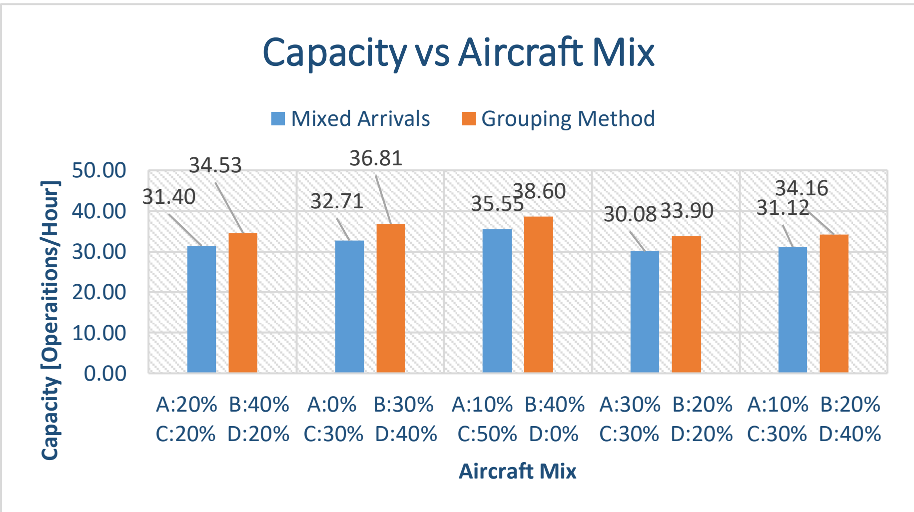


Figure 15 Capacity vs Aircraft Mix

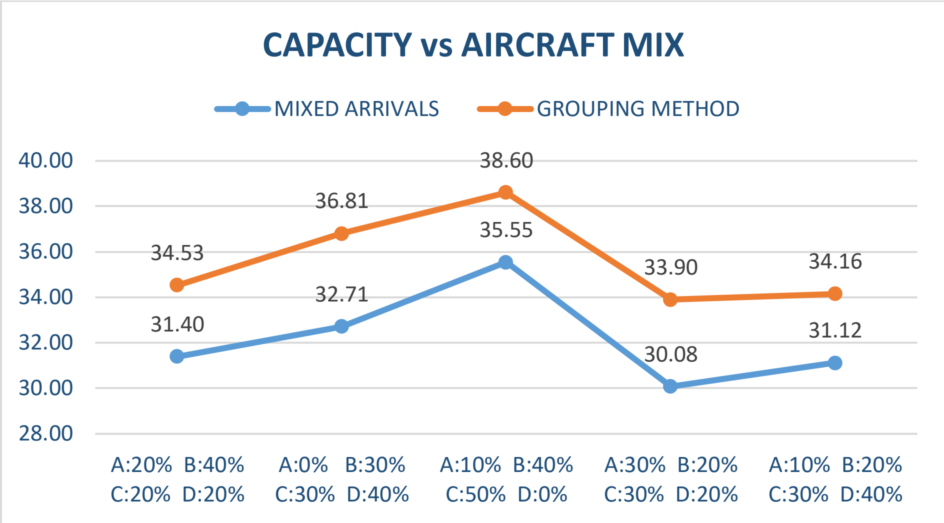


Figure 16 Capacity vs Aircraft Mix

Fig.15 & Fig.16 clearly show that in all five scenarios, the application of the grouping method would be justified as it reduces the average headway between operations which indeed, is transformed in a greater airfield capacity. Between the five scenarios, the 3rd one would obtain the best results with 38,6 operations per hour. The absence of group D in the mix could explain the results as heavy planes generate the highest wake turbulence.

2. Capacity vs Cycle Size

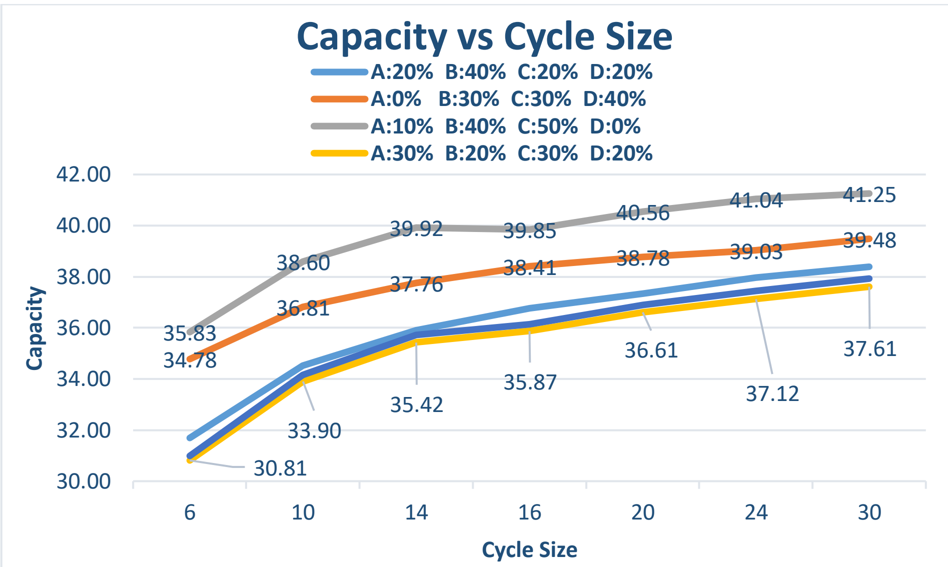


Figure 17 Capacity vs Cycle for Five Aircraft Mix

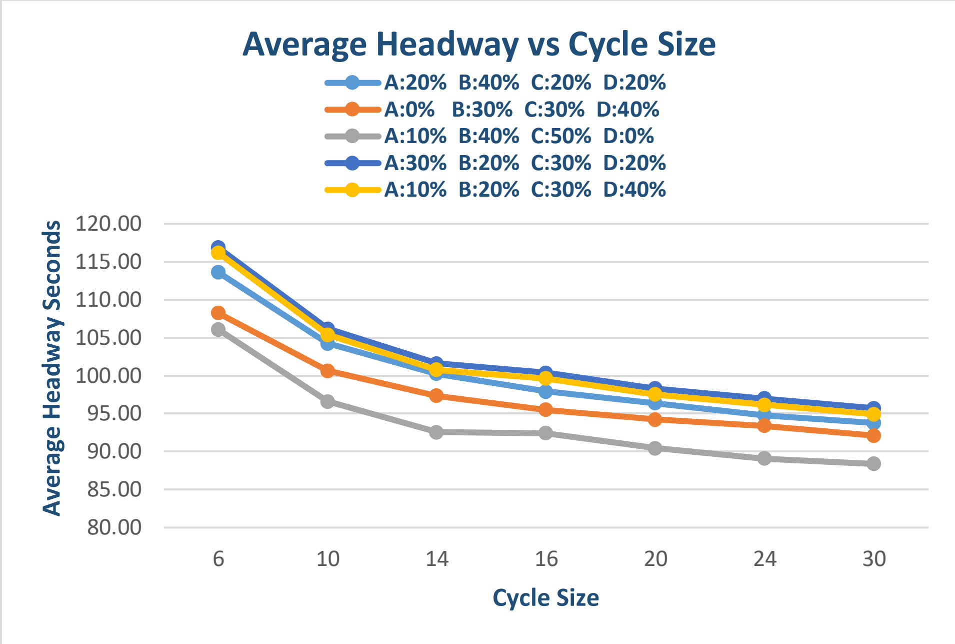


Figure 18 Avg. Headway vs Cycle Size for Five Aircraft Mix

Fig.18 & Fig 19 prove that Capacity increases alongside the cycle size. The five scenarios obtain their highest value for the biggest cycle size computed. This is because the amount of time gained in the grouping method highly relies on the total number of platoon shifts performed within an hour. Therefore, as the cycle size increases, the number of platoon shifts becomes lower resulting in a greater overall airfield capacity.

3. Average Delay vs Aircraft Mix

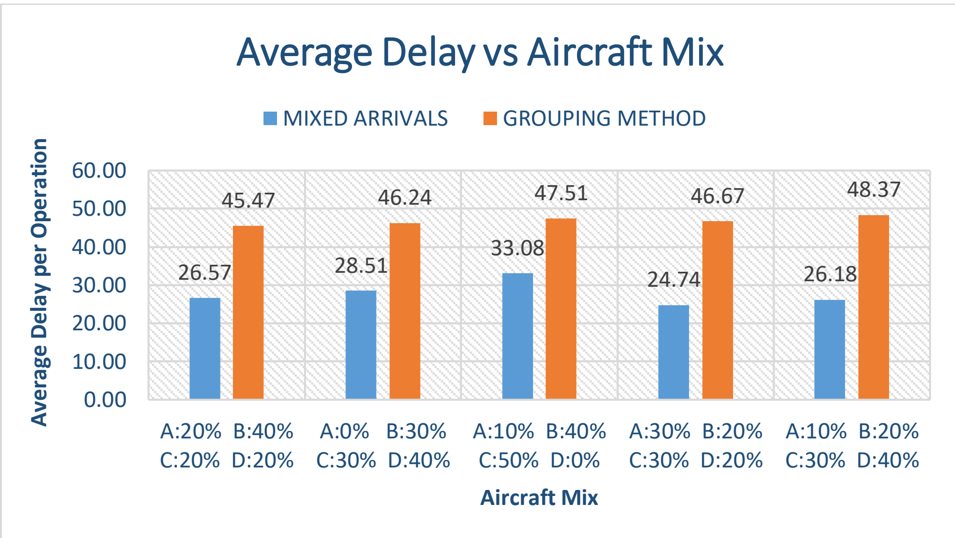


Figure 19 Avg. Delay vs Aircraft Mix

As commented in previous sections, the grouping method would not only have benefits. It produces greater average delay than mixed arrivals. In Fig.20, the difference [seconds] between both approaches is shown. Although all scenarios have similar avg. delay for the grouping method, the 3rd Scenario would have the smallest gap (14.43 seconds) while the 5th one has the largest one (22.19 seconds).

4. **Delay vs Cycle Size**

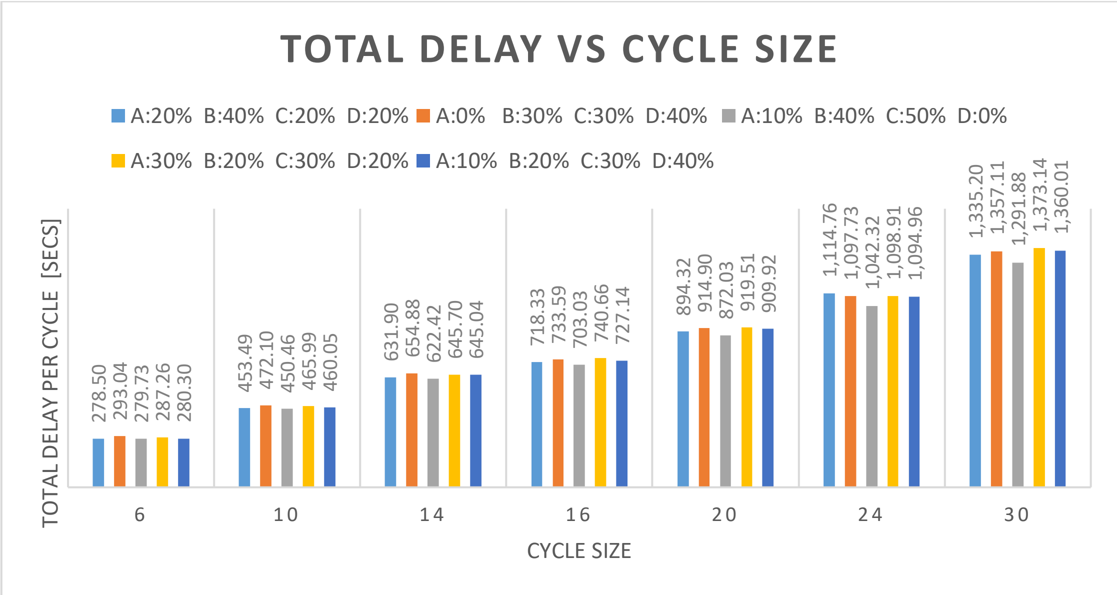


Figure 20 Total Delay vs Cycle Size

Fig. 21 shows graphically the evolution of the total delay per cycle of planes. As expected, the total delay is proportional to the amount of planes per cycle. Nevertheless, it is really interesting to analyze how the average delay varies in relation to the cycle size. The figures below illustrate the fluctuation of the delay.

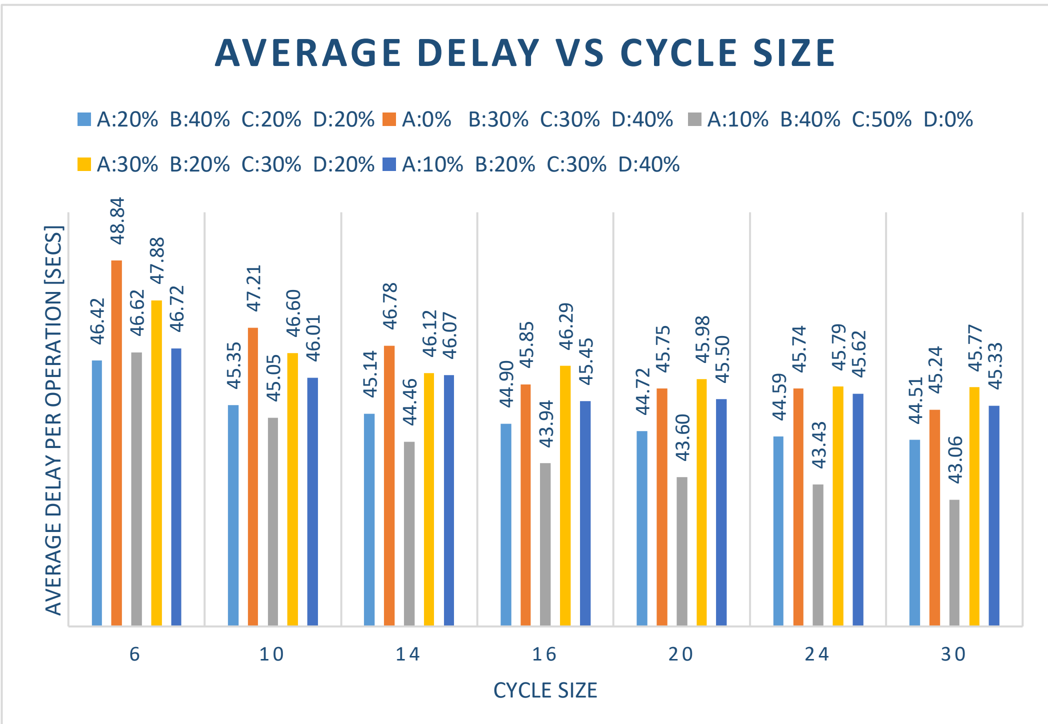


Figure 21 Avg. Delay vs Cycle Size

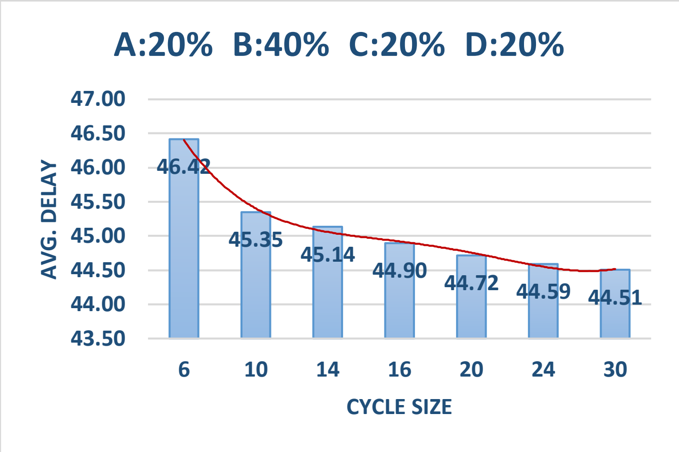


Figure 22 Avg. Delay vs Cycle Size 1st Scenario

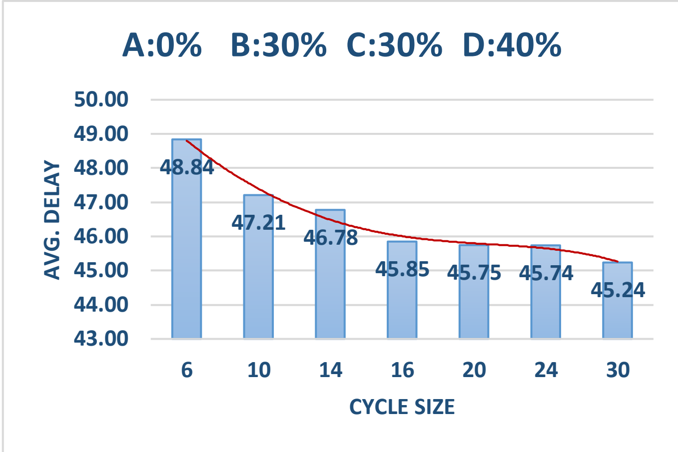


Figure 23 Avg. Delay vs Cycle Size 2nd Scenario

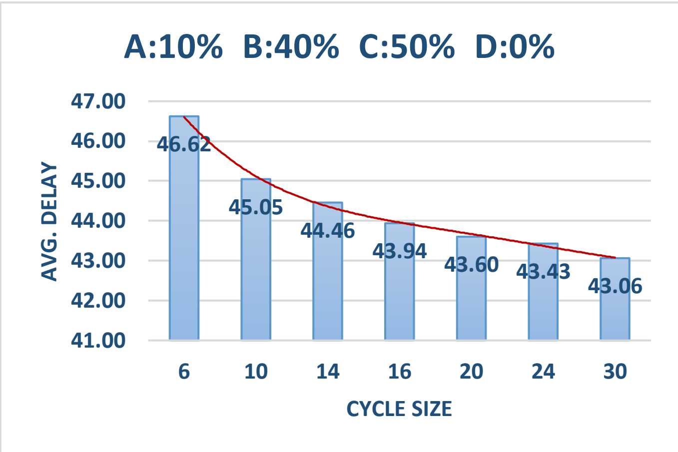


Figure 25 Avg. Delay vs Cycle Size 3rd Scenario

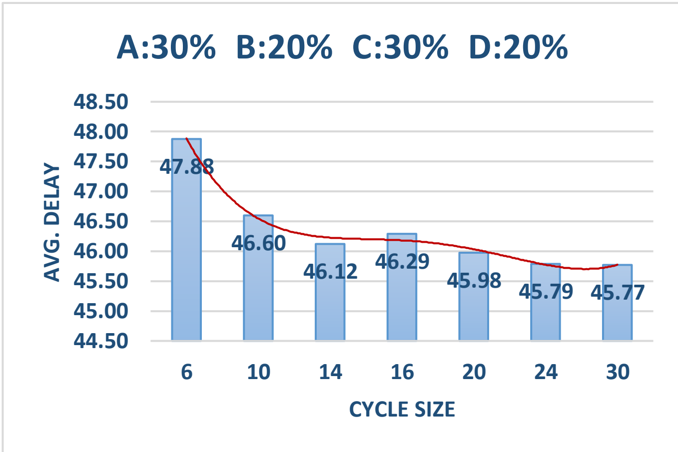


Figure 24 Avg. Delay vs Cycle Size 4th Scenario

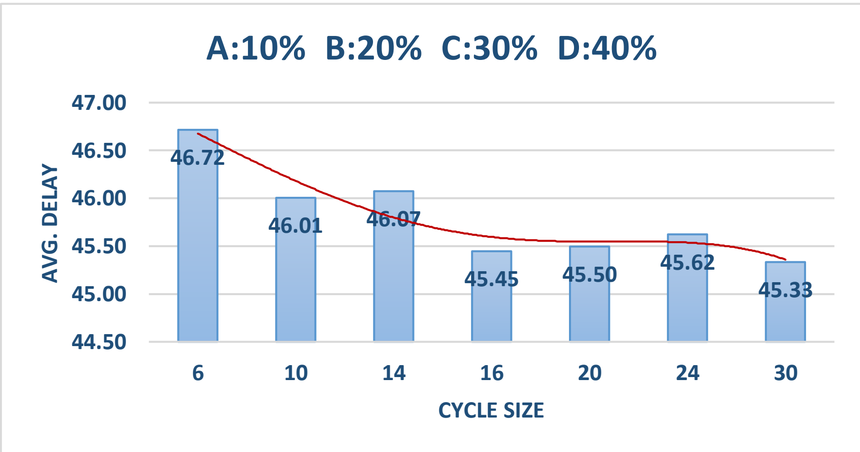


Figure 26 Avg. Delay vs Cycle Size 5th Scenario

The analysis reveals that the average delay remains almost equal for every Cycle Size apart from a small decrease. The 2nd Scenario (Fig.23) has the largest variation, 3.60 secs gap between the cycle size of 6 and 30.

SUMMARY RESULTS

1. Capacity

Aircraft Mix	Mixed Arrivals	Grouping Method
A:40% B:0% C:60% D:0%	30.53 ops/hour	40.51 ops/hour
A:20% B:40% C:20% D:20%	31.40 ops/hour	34.53 ops/hour

Aircraft Mix	A:20% B:40% C:20% D:20%	A:0% B:30% C:30% D:40%	A:10% B:40% C:50% D:0%	A:30% B:20% C:30% D:20%	A:10% B:20% C:30% D:40%
Capacity	34.53	36.81	38.60	33.90	34.16

Table 24 Capacity Analysis Results

2. Average Delay

Aircraft Mix	Mixed Arrivals	Grouping Method
A:40% B:0% C:60% D:0%	25.35 secs/op	42.8 secs/op
A:20% B:40% C:20% D:20%	26.57 secs/op	45.35 secs/op

Aircraft Mix	A:20% B:40% C:20% D:20%	A:0% B:30% C:30% D:40%	A:10% B:40% C:50% D:0%	A:30% B:20% C:30% D:20%	A:10% B:20% C:30% D:40%
Avg. Delay (Mixed)	26.57	28.51	33.08	24.74	26.18
Avg. Delay (Grouping)	45.35	46.24	47.51	46.67	48.37

Table 25 Avg. Delay Analysis Results

3. Takeoffs Between Landings

➢ **2 Aircraft Types:**

Aircraft Type		Leading Aircraft	
		A	**C**
Trailing Aircraft	**A**	NO	YES
	C	NO	NO

➢ **4 Aircraft Mix – 2nd Scenario**

Aircraft Type		Leading Aircraft			
		A	**B**	**C**	**D**
Trailing Aircraft	**A**	NO	YES	YES	YES
	B	NO	NO	YES	YES
	C	NO	NO	NO	YES
	D	NO	NO	NO	NO

Table 26 Takeoffs Analysis Results

CONCLUSIONS

Air transportation is facing a big growth in terms of passenger flow, number of flights, and air traffic congestion. However, this growth sometimes cannot be responded at the same amount and rate. In this light, optimization of the airfield capacity plays a big role in order to allow current airports to squeeze their potential and respond the development of the industry. In this paper, a sensitivity analysis has been performed towards suggesting a possible solution to this growing demand, the grouping method. Therefore, after all the formulation, investigation, and results the following conclusions are made:

Summary of Analysis: Along with this paper, we have gone through different analysis related to factors that affect the airfield capacity or are strongly associated with it. Firstly, we looked at the capacity of one runway whenever is being used for landings. In this light, we developed the formulation for the grouping method and computed this capacity for two cases and aircraft mixes. Next, we studied these cases for a mixed operations runway in order to find if incorporating takeoffs between aircraft shifts could be possible. Then, we analyzed the average delay in two different approaches. We used the Pollaczek-Khinchine formula for queuing models and simulated two scenarios, and then, we developed the formulation for the grouping model in order to compare both situations. After this, we finally performed a sensitivity analysis that combines capacity, delay, and cycle size analysis for five different scenarios.

Summary of Results: According to the results obtained, it can be concluded that the grouping method implies an improvement in capacity for any aircraft mix in comparison to the FCFS. As we have seen, this gain in operations depends essentially on the aircraft mix & cycle size. There are also some other important factors, such as the approaching speed of aircrafts, or the common length approach. However, this benefit in aircraft operations results in a greater average delay that remains almost constant no matter the cycle size as the sensitivity analysis illustrate. This delay could be considered as a drawback for this technique when the airport is not congested and does not need to serve a significant number of aircrafts.

Conclusions and Recommendations about how Airports should operate: Although the study and results reflect a better capacity for the grouping method, it would not make sense for the airport to use this technique whenever it is not congested. Therefore, during periods of low demand, it would be more reasonable for the airport to operate in FCFS as the capacity will not be a problem and the average delay is better. At congested periods the grouping method could help the airport to attend the demand giving substantial progress in the number of operations per hour. The airport will have to choose between increasing the capacity or maintaining the delay regarding their passenger flow, the number of gates, taxiways, and ATM resources available at each concrete airport.

Also, during congested periods the airport should try to incorporate as many takeoffs between landings as possible to maximize the capacity. The grouping method will enable ATM to schedule takeoffs in a more organized and easy way as the cycle sequence would be always the same. In this light, the FCFS would add more complexity and workload for the ATM as the sequence is continuously changing.

Finally, it has to be said that before incorporating the grouping method, it should be analyzed using the ATM software and instruments in order to estimate the real-life pros and cons beyond the ones in this paper.

Recommendations for Further Research: In this paper, some reasonable assumptions have been made to compute the capacity and average delay. The ultimate goal of this first approach was to analyze the efficiency of the grouping method in comparison to the FCFS. In this context, it would be useful to incorporate more variables and complexity that affect this capacity in real life, such as wind speed, touchdown percentage, incomplete approaches, ATM workload or more airport layouts (more runways). Also, it could be interesting to develop software available to organize the upcoming arrivals and automatically switch between FCFS and Grouping according to the needs at the time. This paper could be used as a baseline study for future and deeper analysis of the grouping method as it initially justifies its efficacy.

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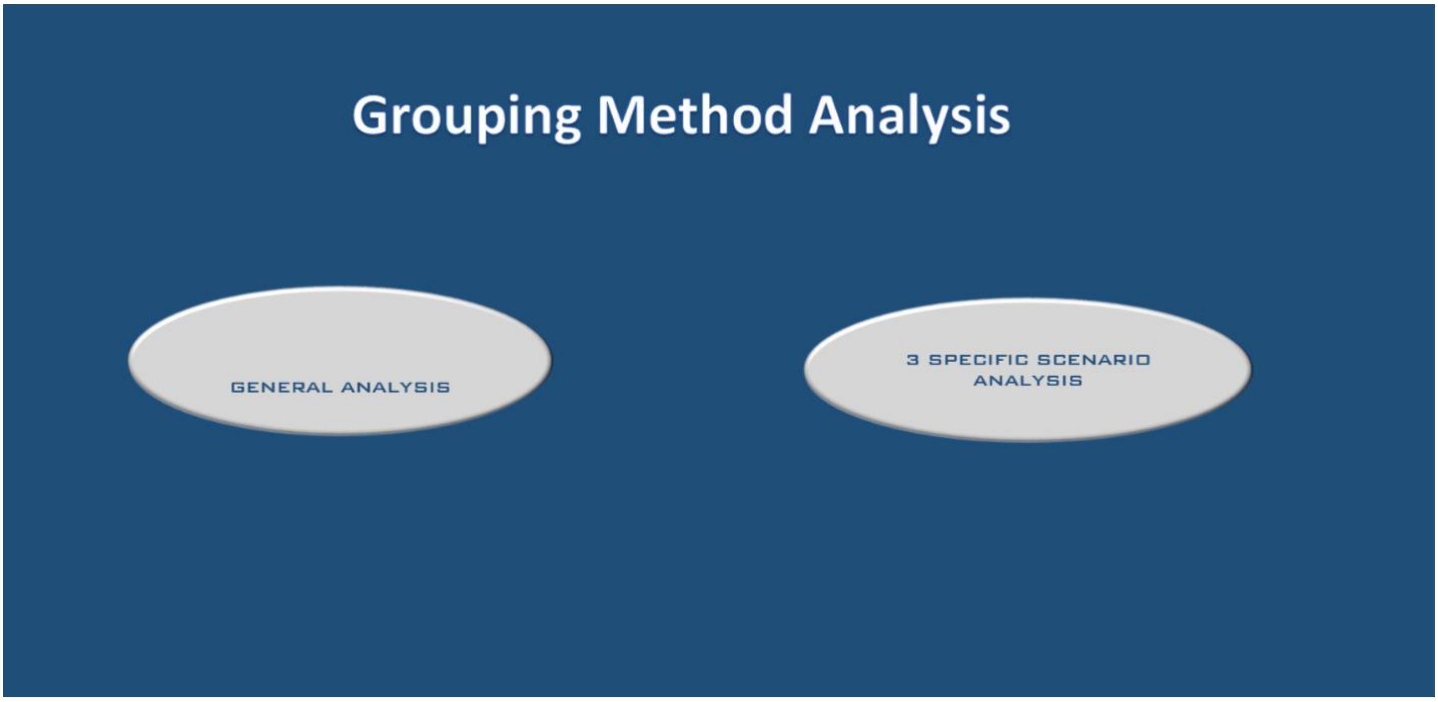
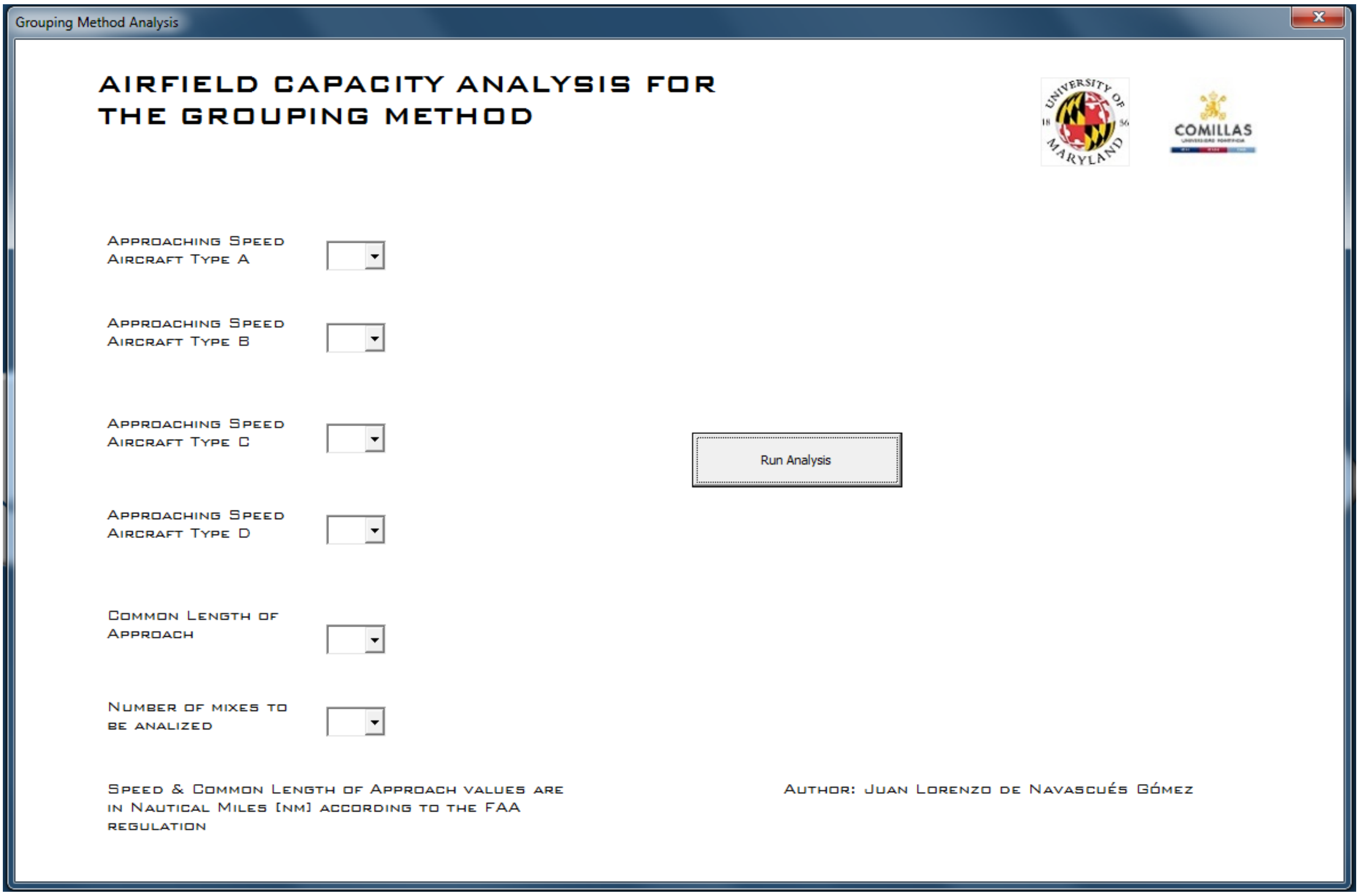
APPENDIX

General Analysis





AIRFIELD CAPACITY ANALYSIS FOR THE GROUPING METHOD

Approaching Speed Aircraft Type A: 85

Approaching Speed Aircraft Type B: 100

Approaching Speed Aircraft Type C: 130

Run Analysis

Approaching Speed Aircraft Type D: 145

Common Length of Approach: 5

Number of mixes to be analized: 40

Speed & Common Length of Approach values are in Nautical Miles [NM] according to the FAA regulation

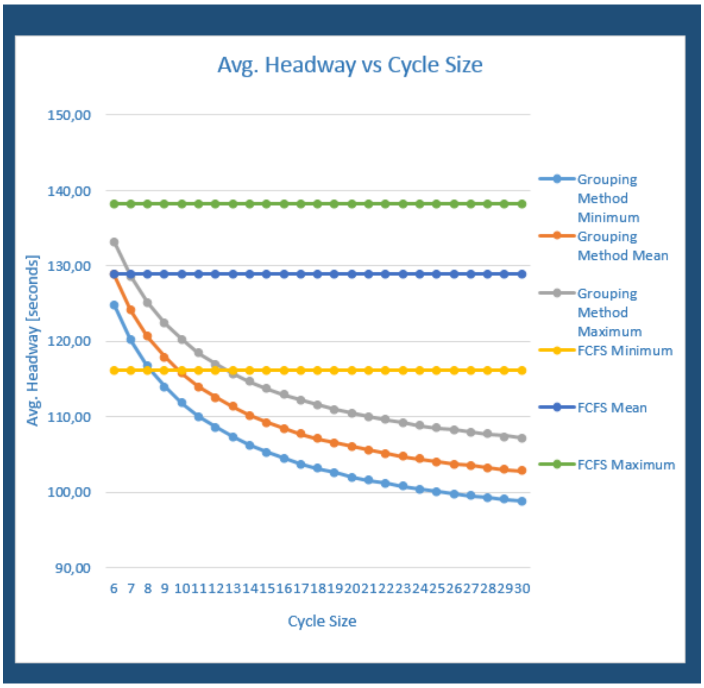
Author: Juan Lorenzo de Navascués Gómez

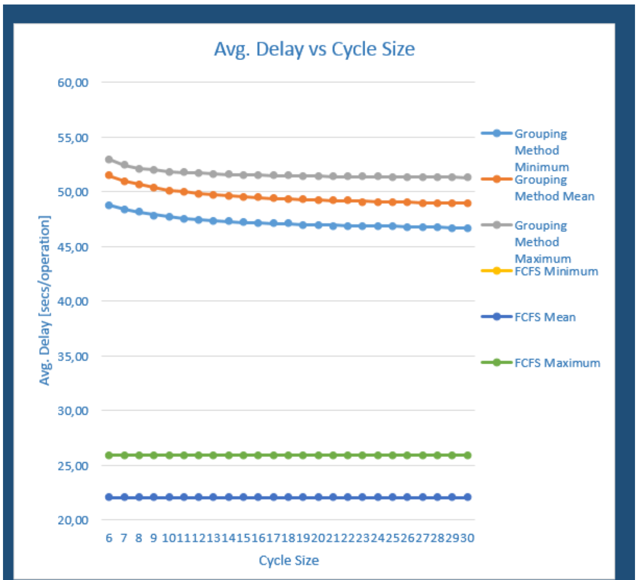
Aircraft Mix	Cycle Size 6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
%A: 20 %B: 50 %C: 10 %D: 20	126,87	122,22	118,74	116,03	113,86	112,09	110,61	109,36	108,28	107,35	106,54	105,82	105,19	104,62	104,10	103,64	103,22	102,83	102,48	102,15	101,85	101,57	101,32	101,07	100,85
%A: 40 %B: 30 %C: 10 %D: 20	130,04	125,40	121,91	119,20	117,04	115,26	113,78	112,53	111,46	110,53	109,72	109,00	108,36	107,79	107,28	106,81	106,39	106,01	105,65	105,33	105,03	104,75	104,49	104,25	104,03
%A: 50 %B: 10 %C: 30 %D: 10	129,3169	124,67095	121,1865	118,47636	116,30825	114,53435	113,05609	111,80526	110,73312	109,80393	108,99089	108,2735	107,63582	107,06527	106,55177	106,08718	105,66482	105,27919	104,92569	104,60047	104,30027	104,02231	103,7642	103,5239	103,29961
%A: 60 %B: 20 %C: 10 %D: 10	132,28975	127,6438	124,15935	121,44921	119,2811	117,5072	116,02894	114,77811	113,70597	112,77678	111,96374	111,24635	110,60868	110,03812	109,52462	109,06003	108,63767	108,25204	107,89854	107,57333	107,27313	106,99516	106,73706	106,49675	106,27246
%A: 40 %B: 10 %C: 20 %D: 30	130,28304	125,6371	122,15264	119,4425	117,2744	115,50049	114,02223	112,7714	111,69926	110,77007	109,95703	109,23964	108,60197	108,03141	107,51791	107,05332	106,63096	106,24533	105,89183	105,56662	105,26642	104,98845	104,73035	104,49004	104,26575
%A: 20 %B: 30 %C: 30 %D: 20	125,48323	120,83728	117,35282	114,64269	112,47458	110,70068	109,22242	107,97159	106,89945	105,97026	105,15722	104,43983	103,80215	103,2316	102,7181	102,25351	101,83115	101,44551	101,09202	100,7668	100,4666	100,18864	99,930533	99,690225	99,465939
%A: 50 %B: 30 %C: 10 %D: 10	130,70151	126,05557	122,57111	119,86098	117,69287	115,91896	114,44071	113,18988	112,11774	111,18855	110,37551	109,65812	109,02044	108,44989	107,93639	107,47179	107,04943	106,6638	106,31031	105,98509	105,68489	105,40693	105,14882	104,90851	104,68423
%A: 40 %B: 40 %C: 10 %D: 10	129,11328	124,46733	120,98288	118,27274	116,10463	114,33073	112,85247	111,60164	110,5295	109,60031	108,78727	108,06988	107,4322	106,86165	106,34815	105,88356	105,4612	105,07557	104,72207	104,39685	104,09665	103,81869	103,56058	103,32028	103,09599
%A: 40 %B: 20 %C: 10 %D: 30	130,97535	126,3294	122,84494	120,13481	117,9667	116,1928	114,71454	113,46371	112,39157	111,46238	110,64934	109,93195	109,29427	108,72372	108,21022	107,74563	107,32327	106,93764	106,58414	106,25892	105,95872	105,68076	105,42265	105,18235	104,95806
%A: 60 %B: 10 %C: 20 %D: 10	131,59744	126,9515	123,46704	120,7569	118,5888	116,81489	115,33664	114,0858	113,01366	112,08447	111,27143	110,55405	109,91637	109,34581	108,83231	108,36772	107,94536	107,55973	107,20623	106,88102	106,58082	106,30286	106,04475	105,80444	105,58015
%A: 20 %B: 20 %C: 40 %D: 20	124,79092	120,14497	116,66052	113,95038	111,78227	110,00837	108,53011	107,27928	106,20714	105,27795	104,46491	103,74752	103,10985	102,53929	102,02579	101,5612	101,13884	100,75321	100,39971	100,0745	99,774296	99,496333	99,238225	98,997918	98,773631
%A: 30 %B: 20 %C: 40 %D: 10	125,44812	120,80218	117,31772	114,60758	112,43948	110,66557	109,18731	107,93648	106,86434	105,93515	105,12211	104,40472	103,76705	103,19649	102,68299	102,2184	101,79604	101,41041	101,05691	100,7317	100,4315	100,15353	99,895426	99,655119	99,430832
%A: 20 %B: 60 %C: 10 %D: 10	125,93681	121,29086	117,80641	115,09627	112,92816	111,15426	109,676	108,42517	107,35303	106,42384	105,6108	104,89341	104,25573	103,68518	103,17168	102,70709	102,28473	101,8991	101,5456	101,22038	100,92018	100,64222	100,38411	100,14381	99,919519
%A: 20 %B: 10 %C: 20 %D: 50	128,96864	124,32269	120,83824	118,1281	115,95999	114,18609	112,70783	111,457	110,38486	109,45567	108,64263	107,92524	107,28756	106,71701	106,20351	105,73892	105,31656	104,93093	104,57743	104,25221	103,95201	103,67405	103,41594	103,17564	102,95135
%A: 20 %B: 30 %C: 20 %D: 30	127,10657	122,46062	118,97617	116,26603	114,09792	112,32402	110,84576	109,59493	108,52279	107,5936	106,78056	106,06317	105,4255	104,85494	104,34144	103,87685	103,45449	103,06886	102,71536	102,39015	102,08995	101,81198	101,55388	101,31357	101,08928
%A: 50 %B: 20 %C: 10 %D: 20	131,63255	126,9866	123,50215	120,79201	118,6239	116,85	115,37174	114,12091	113,04877	112,11958	111,30654	110,58915	109,95147	109,38092	108,86742	108,40283	107,98047	107,59484	107,24134	106,91612	106,61592	106,33796	106,07985	105,83955	105,61526
%A: 20 %B: 30 %C: 10 %D: 40	128,72991	124,08397	120,59951	117,88937	115,72127	113,94736	112,46911	111,21827	110,14613	109,21694	108,4039	107,68652	107,04884	106,47828	105,96478	105,50019	105,07783	104,6922	104,3387	104,01349	103,71329	103,43533	103,17722	102,93691	102,71262
%A: 40 %B: 20 %C: 20 %D: 20	129,352	124,70606	121,2216	118,51147	116,34336	114,56945	113,0912	111,84037	110,76823	109,83904	109,026	108,30861	107,67093	107,10038	106,58688	106,12228	105,69992	105,31429	104,9608	104,63558	104,33538	104,05742	103,79931	103,559	103,33472
%A: 50 %B: 20 %C: 20 %D: 10	130,00921	125,36326	121,8788	119,16867	117,00056	115,22666	113,7484	112,49757	111,42543	110,49624	109,6832	108,96581	108,32813	107,75758	107,24408	106,77948	106,35713	105,97149	105,618	105,29278	104,99258	104,71462	104,45651	104,2162	103,99192
%A: 20 %B: 50 %C: 10 %D: 20	126,86784	122,2219	118,73744	116,02731	113,8592	112,08529	110,60704	109,35621	108,28406	107,35488	106,54184	105,82445	105,18677	104,61621	104,10271	103,63812	103,21576	102,83013	102,47663	102,15142	101,85122	101,57326	101,31515	101,07484	100,85055
%A: 20 %B: 50 %C: 20 %D: 10	125,2445	120,59856	117,1141	114,40396	112,23586	110,46195	108,98369	107,73286	106,66072	105,73153	104,91849	104,20111	103,56343	102,99287	102,47937	102,01478	101,59242	101,20679	100,85329	100,52808	100,22788	99,949914	99,691806	99,451499	99,227212
%A: 30 %B: 30 %C: 10 %D: 30	129,38711	124,74117	121,25671	118,54658	116,37847	114,60456	113,12631	111,87548	110,80333	109,87415	109,06111	108,34372	107,70604	107,13548	106,62198	106,15739	105,73503	105,3494	104,9959	104,67069	104,37049	104,09253	103,83442	103,59411	103,36982
%A: 40 %B: 30 %C: 20 %D: 10	128,42097	123,77503	120,29057	117,58043	115,41233	113,63842	112,16017	110,90933	109,83719	108,908	108,09496	107,37758	106,7399	106,16934	105,65584	105,19125	104,76889	104,38326	104,02976	103,70455	103,40435	103,12638	102,86828	102,62797	102,40368
%A: 60 %B: 10 %C: 10 %D: 20	133,22078	128,57484	125,09038	122,38025	120,21214	118,43823	116,95998	115,70915	114,63701	113,70782	112,89478	112,17739	111,53971	110,96916	110,45566	109,99106	109,5687	109,18307	108,82958	108,50436	108,20416	107,9262	107,66809	107,42778	107,2035
%A: 10 %B: 20 %C: 20 %D: 50	127,3804	122,73446	119,25	116,53987	114,37176	112,59785	111,1196	109,86877	108,79663	107,86744	107,0544	106,33701	105,69933	105,12877	104,61528	104,15068	103,72832	103,34269	102,98919	102,66398	102,36378	102,08582	101,82771	101,5874	101,36311

Capacity Aircraft Mix	Cycle Size 6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	FCFS
%A: 20 %B: 50 %C: 10 %D: 20	28,38	29,45	30,32	31,03	31,62	32,12	32,55	32,92	33,25	33,53	33,79	34,02	34,22	34,41	34,58	34,74	34,88	35,01	35,13	35,24	35,35	35,44	35,53	35,62	35,70	28,86
%A: 40 %B: 30 %C: 10 %D: 20	27,68	28,71	29,53	30,20	30,76	31,23	31,64	31,99	32,30	32,57	32,81	33,03	33,22	33,40	33,56	33,70	33,84	33,96	34,07	34,18	34,28	34,37	34,45	34,53	34,61	27,40
%A: 50 %B: 10 %C: 30 %D: 10	27,838589	28,876012	29,70628	30,385808	30,952231	31,431619	31,8426	32,198842	32,510598	32,785711	33,030283	33,249132	33,446113	33,624349	33,786393	33,934356	34,069997	34,194793	34,309996	34,41667	34,515729	34,60796	34,694045	34,77458	34,850083	27,529862
%A: 60 %B: 20 %C: 10 %D: 10	27,212993	28,203484	28,994998	29,64202	30,180807	30,636421	31,026741	31,364865	31,660606	31,921464	32,153266	32,360611	32,547176	32,715935	32,869321	33,009344	33,137677	33,255725	33,364677	33,465545	33,559197	33,646381	33,727743	33,803849	33,875192	28,521446
%A: 40 %B: 10 %C: 20 %D: 30	27,632146	28,653958	29,471324	30,140025	30,697238	31,168699	31,572789	31,922987	32,229398	32,499753	32,740061	32,955069	33,148571	33,323641	33,482793	33,628103	33,761302	33,883843	33,996957	34,10169	34,198941	34,289485	34,373991	34,453045	34,527157	26,032337
%A: 20 %B: 30 %C: 30 %D: 20	28,689093	29,79213	30,676722	31,401915	32,007231	32,520126	32,960265	33,342104	33,676506	33,971795	34,234454	34,469607	34,681361	34,873043	35,047377	35,206617	35,352641	35,48703	35,61112	35,726052	35,832803	35,932217	36,025026	36,111865	36,193294	28,349394
%A: 50 %B: 30 %C: 10 %D: 10	27,543675	28,558833	29,370705	30,034796	30,588089	31,056178	31,457338	31,804964	32,109104	32,377435	32,615932	32,829307	33,021331	33,195056	33,352979	33,497162	33,629323	33,750907	33,863133	33,967042	34,063526	34,153353	34,237189	34,315614	34,389135	28,877545
%A: 40 %B: 40 %C: 10 %D: 10	27,882492	28,923251	29,756277	30,438121	31,006514	31,487598	31,900054	32,25759	32,57049	32,846622	33,092107	33,311778	33,509505	33,688419	33,851082	33,999613	34,135778	34,261057	34,376708	34,483798	34,583244	34,675836	34,76226	34,843112	34,918914	29,394336
%A: 40 %B: 20 %C: 10 %D: 30	27,486089	28,496929	29,305235	29,966335	30,517086	30,982988	31,382246	31,728206	32,030872	32,297892	32,535214	32,747531	32,938597	33,11145	33,268577	33,412029	33,543519	33,664481	33,776132	33,879508	33,975494	34,064857	34,148258	34,226276	34,299415	26,127628
%A: 60 %B: 10 %C: 20 %D: 10	27,356155	28,357287	29,15758	29,81196	30,356999	30,817989	31,212979	31,555197	31,854555	32,118632	32,353317	32,563259	32,752174	32,923071	33,078411	33,220225	33,350206	33,469776	33,580137	33,682314	33,777185	33,865506	33,947933	34,025037	34,097318	27,653082
%A: 20 %B: 20 %C: 40 %D: 20	28,848253	29,9638	30,85877	31,592698	32,205464	32,724783	33,170517	33,557271	33,896026	34,195194	34,461332	34,699623	34,914222	35,108493	35,285195	35,446608	35,594634	35,730873	35,856677	35,973202	36,081437	36,182238	36,276344	36,364401	36,446974	28,647083
%A: 30 %B: 20 %C: 40 %D: 10	28,697122	29,800788	30,685902	31,411534	32,017225	32,530443	32,970863	33,352949	33,68757	33,983054	34,245887	34,481198	34,693095	34,884907	35,05936	35,218709	35,364834	35,499315	35,623491	35,738503	35,845329	35,944812	36,037686	36,124587	36,206074	28,622059
%A: 20 %B: 60 %C: 10 %D: 10	28,585765	29,680719	30,55861	31,278164	31,878673	32,387423	32,823953	33,202622	33,534219	33,827007	34,087422	34,320554	34,530475	34,720488	34,893296	35,051136	35,19587	35,329067	35,452053	35,565959	35,671754	35,770275	35,862248	35,948304	36,028996	30,985557
%A: 20 %B: 10 %C: 20 %D: 50	27,913763	28,956902	29,791895	30,47539	31,04519	31,527484	31,940992	32,299451	32,613168	32,890027	33,136164	33,356422	33,554681	33,734079	33,897185	34,046122	34,182659	34,308284	34,424254	34,531641	34,631363	34,724214	34,81088	34,891958	34,967973	27,231644
%A: 20 %B: 30 %C: 20 %D: 30	28,32269	29,397204	30,258161	30,963472	31,551845	32,050135	32,477561	32,848234	33,172755	33,459238	33,714001	33,942035	34,147338	34,333146	34,502111	34,656423	34,79791	34,928106	35,048312	35,159634	35,263022	35,359296	35,449164	35,533247	35,612084	27,47102
%A: 50 %B: 20 %C: 10 %D: 20	27,348859	28,349447	29,149291	29,803295	30,348015	30,80873	31,203481	31,545489	31,844663	32,108575	32,343113	32,552921	32,741716	32,912504	33,067744	33,209466	33,339363	33,458855	33,569144	33,671254	33,766063	33,854326	33,936698	34,013751	34,085983	26,910367
%A: 20 %B: 30 %C: 10 %D: 40	27,965529	29,012612	29,850868	30,537103	31,109234	31,593536	32,00879	32,368781	32,683853	32,961918	33,209136	33,430369	33,62951	33,809711	33,973551	34,123161	34,260319	34,386516	34,503016	34,610896	34,711078	34,804357	34,891424	34,972878	35,049246	26,823649
%A: 40 %B: 20 %C: 20 %D: 20	27,831034	28,867883	29,697677	30,376807	30,942892	31,421988	31,832716	32,188735	32,500294	32,775232	33,019647	33,238355	33,435208	33,613327	33,775265	33,92313	34,058681	34,183394	34,29852	34,405123	34,504115	34,596284	34,682311	34,762791	34,838243	26,959473
%A: 50 %B: 20 %C: 20 %D: 10	27,690347	28,716547	29,53754	30,209283	30,769083	31,242771	31,648797	32,000691	32,308604	32,580294	32,8218	33,037886	33,232365	33,408323	33,568287	33,714342	33,848226	33,9714	34,0851	34,190378	34,288136	34,379154	34,464103	34,543572	34,618075	28,00845
%A: 20 %B: 50 %C: 10 %D: 20	28,375985	29,454624	30,318996	31,027179	31,617999	32,118398	32,547658	32,919942	33,245889	33,533642	33,789544	34,018604	34,224837	34,411492	34,581231	34,736253	34,878394	35,009194	35,129959	35,241801	35,345674	35,4424	35,532692	35,617172	35,696383	28,863616
%A: 20 %B: 50 %C: 20 %D: 10	28,743777	29,851104	30,739254	31,467441	32,075311	32,590408	33,032464	33,415987	33,751881	34,048499	34,312349	34,548578	34,761306	34,953875	35,129021	35,289005	35,435715	35,570737	35,695414	35,810891	35,918151	36,01804	36,111293	36,19855	36,28037	30,05872
%A: 30 %B: 30 %C: 10 %D: 30	27,823482	28,859759	29,689079	30,367811	30,933557	31,412362	31,822837	32,178634	32,489997	32,76476	33,009018	33,227584	33,42431	33,602312	33,764144	33,911911	34,047372	34,172003	34,287052	34,393583	34,492509	34,584616	34,670585	34,75101	34,826411	26,750495
%A: 40 %B: 30 %C: 20 %D: 10	28,032805	29,085027	29,927533	30,617339	31,192509	31,679427	32,096957	32,458945	32,775783	33,055422	33,304049	33,526553	33,726845	33,908094	34,072891	34,223379	34,361345	34,488289	34,605481	34,714004	34,814784	34,908622	34,996212	35,078157	35,154986	28,51585
%A: 60 %B: 10 %C: 10 %D: 20	27,022811	27,999257	28,779191	29,416512	29,947059	30,39559	30,77976	31,112493	31,403472	31,660092	31,888101	32,092029	32,275501	32,441447	32,592265	32,729932	32,856098	32,972144	33,079243	33,17839	33,27044	33,356127	33,436091	33,510885	33,580995	26,563463
%A: 10 %B: 20 %C: 20 %D: 50	28,261804	29,331616	30,188679	30,890717	31,476302	31,972191	32,397526	32,766364	33,089262	33,374298	33,627764	33,85463	34,058873	34,243717	34,411801	34,565304	34,706047	34,835555	34,955123	35,065853	35,16869	35,264448	35,353835	35,437465	35,515878	28,292133

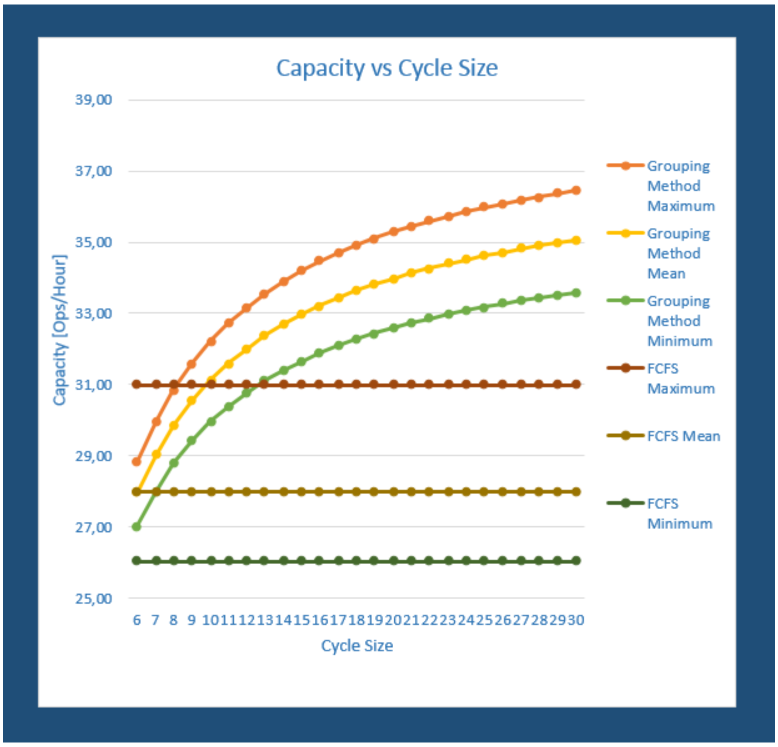
Average Delay	Cycle Size												
Aircraft Mix	6	7	8	9	10	11	12	13	14	15	16	17	18
%A: 20 %B: 50 %C: 10 %D: 20	50,29	49,78	49,40	49,11	48,88	48,70	48,55	48,42	48,31	48,22	48,13	48,06	48,00
%A: 40 %B: 30 %C: 10 %D: 20	52,51	51,99	51,60	51,31	51,08	50,89	50,73	50,60	50,49	50,40	50,32	50,24	50,18
%A: 50 %B: 10 %C: 30 %D: 10	51,575778	51,152351	50,846758	50,616821	50,438104	50,29554	50,179373	50,083026	50,001913	49,932744	49,873105	49,821182	49,77559
%A: 60 %B: 20 %C: 10 %D: 10	52,330794	52,008138	51,784524	51,622465	51,500814	51,406869	51,332602	51,272727	51,223643	51,182822	51,148445	51,119175	51,094011
%A: 40 %B: 10 %C: 20 %D: 30	52,6576	52,14282	51,76463	51,475587	51,247797	51,063832	50,912263	50,785293	50,677428	50,584688	50,50412	50,433491	50,371079
%A: 20 %B: 30 %C: 30 %D: 20	50,654289	50,042942	49,584663	49,228375	48,943447	48,710395	48,516237	48,351988	48,211231	48,089265	47,982561	47,888425	47,804759
%A: 50 %B: 30 %C: 10 %D: 10	52,201868	51,777213	51,471322	51,24155	51,063226	50,921166	50,805548	50,70976	50,629196	50,560558	50,501424	50,44998	50,40484
%A: 40 %B: 40 %C: 10 %D: 10	51,541493	51,065032	50,716887	50,452062	50,244221	50,076983	49,939645	49,824932	49,727737	49,64437	49,572103	49,508876	49,453106
%A: 40 %B: 20 %C: 10 %D: 30	52,971846	52,455643	52,076681	51,787224	51,559229	51,375183	51,223608	51,096678	50,988882	50,896228	50,815755	50,745226	50,682916
%A: 60 %B: 10 %C: 20 %D: 10	52,044089	51,725075	51,504067	51,343961	51,223826	51,131089	51,057807	50,998751	50,950358	50,910127	50,876261	50,847437	50,822665
%A: 20 %B: 20 %C: 40 %D: 20	50,021743	49,427721	48,982912	48,63741	48,361319	48,135645	47,947741	47,788862	47,652768	47,534888	47,431796	47,340874	47,260089
%A: 30 %B: 20 %C: 40 %D: 10	50,162831	49,607376	49,193901	48,87433	48,620042	48,412946	48,241059	48,096127	47,972287	47,865256	47,771837	47,689593	47,616636
%A: 20 %B: 60 %C: 10 %D: 10	48,842407	48,429074	48,129835	47,904071	47,728181	47,587579	47,472797	47,377439	47,297038	47,228382	47,169111	47,11745	47,07204
%A: 20 %B: 10 %C: 20 %D: 50	51,49273	51,017976	50,671123	50,407309	50,200284	50,033716	49,896939	49,782704	49,68592	49,602911	49,530957	49,468008	49,412486
%A: 20 %B: 30 %C: 20 %D: 30	51,490946	50,89169	50,444088	50,097145	49,820396	49,594529	49,406714	49,248095	49,112362	48,994902	48,892261	48,801804	48,721484
%A: 50 %B: 20 %C: 10 %D: 20	52,889813	52,442114	52,118256	51,874061	51,683894	51,531929	51,407902	51,304883	51,218033	51,14388	51,079868	51,024077	50,97504
%A: 20 %B: 30 %C: 10 %D: 40	51,798562	51,259057	50,860242	50,553814	50,311213	50,114499	49,951852	49,815175	49,698737	49,598373	49,510985	49,434218	49,366254
%A: 40 %B: 20 %C: 20 %D: 20	52,467347	51,923132	51,520889	51,211862	50,967225	50,768876	50,604888	50,467091	50,349706	50,248531	50,160439	50,083056	50,014549
%A: 50 %B: 20 %C: 20 %D: 10	52,177511	51,73214	51,409335	51,16552	50,975367	50,823212	50,698883	50,595504	50,508268	50,43372	50,369316	50,313143	50,263737
%A: 20 %B: 50 %C: 10 %D: 20	50,288537	49,778228	49,401761	49,113013	48,88476	48,699931	48,547293	48,419163	48,310111	48,216196	48,134485	48,062757	47,999295
%A: 20 %B: 50 %C: 20 %D: 10	49,556593	49,045576	48,667622	48,377102	48,147018	47,960401	47,806066	47,676348	47,565821	47,470537	47,387561	47,314662	47,250115
%A: 30 %B: 30 %C: 10 %D: 30	52,366095	51,805066	51,389388	51,069376	50,815591	50,609504	50,438886	50,295345	50,172935	50,067326	49,975294	49,894387	49,822708
%A: 40 %B: 30 %C: 20 %D: 10	51,771406	51,249224	50,864106	50,56879	50,335388	50,146418	49,990382	49,859413	49,747956	49,651977	49,568478	49,495184	49,430341
%A: 60 %B: 10 %C: 10 %D: 20	52,714689	52,389796	52,1648	52,001847	51,879601	51,78525	51,710701	51,650628	51,601405	51,560485	51,52604	51,496724	51,471529
%A: 10 %B: 20 %C: 20 %D: 50	50,790515	50,312562	49,962302	49,695192	49,485097	49,315717	49,176381	49,059822	48,960926	48,875996	48,80229	48,737739	48,680747

Average Delay	Cycle Size												
Aircraft Mix	19	20	21	22	23	24	25	26	27	28	29	30	FCFS
%A: 20 %B: 50 %C: 10 %D: 20	47,94	47,89	47,85	47,80	47,77	47,73	47,70	47,67	47,65	47,62	47,60	47,58	23,14
%A: 40 %B: 30 %C: 10 %D: 20	50,12	50,07	50,03	49,99	49,95	49,91	49,88	49,85	49,82	49,80	49,78	49,76	21,32
%A: 50 %B: 10 %C: 30 %D: 10	49,735253	49,699325	49,667129	49,638118	49,611848	49,587953	49,566127	49,546115	49,527702	49,510706	49,494971	49,480363	21,478231
%A: 60 %B: 20 %C: 10 %D: 10	51,072188	51,053115	51,036329	51,021461	51,008217	50,996357	50,985684	50,976037	50,967282	50,959306	50,952014	50,945325	22,706125
%A: 40 %B: 10 %C: 20 %D: 30	50,315536	50,265793	50,220992	50,180433	50,143545	50,109852	50,078958	50,050529	50,024283	49,999978	49,977407	49,956392	19,714225
%A: 20 %B: 30 %C: 30 %D: 20	47,729909	47,662552	47,601616	47,546224	47,495654	47,449301	47,40666	47,367301	47,33086	47,297024	47,265524	47,236125	22,489488
%A: 50 %B: 30 %C: 10 %D: 10	50,364929	50,329401	50,297581	50,268925	50,242989	50,219408	50,197878	50,178145	50,159997	50,143251	50,127752	50,113368	23,159412
%A: 40 %B: 40 %C: 10 %D: 10	49,403557	49,359252	49,319404	49,283378	49,250653	49,220797	49,19345	49,168312	49,145125	49,123673	49,103768	49,08525	23,829289
%A: 40 %B: 20 %C: 10 %D: 30	50,627474	50,577831	50,533127	50,492662	50,455865	50,422259	50,391449	50,363101	50,336932	50,312701	50,290201	50,269254	19,823384
%A: 60 %B: 10 %C: 20 %D: 10	50,801191	50,782429	50,765923	50,751308	50,738293	50,726642	50,71616	50,70669	50,698097	50,690271	50,683118	50,676559	21,628137
%A: 20 %B: 20 %C: 40 %D: 20	47,187835	47,122829	47,064032	47,010597	46,961821	46,917121	46,876006	46,838063	46,802937	46,770326	46,73997	46,711642	22,865291
%A: 30 %B: 20 %C: 40 %D: 10	47,551479	47,492936	47,440052	47,392043	47,348267	47,308187	47,271356	47,237394	47,205979	47,176835	47,149724	47,124441	22,833523
%A: 20 %B: 60 %C: 10 %D: 10	47,031825	46,995974	46,963819	46,934824	46,908549	46,884632	46,862773	46,842719	46,824257	46,807206	46,791413	46,776743	25,986169
%A: 20 %B: 10 %C: 20 %D: 50	49,36316	49,319054	49,279389	49,243528	49,210954	49,181237	49,154019	49,128999	49,105923	49,084573	49,064763	49,046334	21,118496
%A: 20 %B: 30 %C: 20 %D: 30	48,64969	48,585134	48,526773	48,473759	48,425388	48,381077	48,340335	48,302748	48,267964	48,235679	48,205636	48,177607	21,406909
%A: 50 %B: 20 %C: 10 %D: 20	50,931614	50,8929	50,858179	50,82687	50,798498	50,772672	50,749068	50,727413	50,707477	50,689065	50,672009	50,656167	20,735731
%A: 20 %B: 30 %C: 10 %D: 40	49,305666	49,251319	49,202298	49,157861	49,117393	49,080388	49,04642	49,01513	48,986216	48,959416	48,934508	48,911298	20,633254
%A: 40 %B: 20 %C: 20 %D: 20	49,953479	49,898701	49,849293	49,804504	49,763719	49,726423	49,692189	49,660655	49,631515	49,604506	49,579404	49,556014	20,793917
%A: 50 %B: 20 %C: 20 %D: 10	50,219958	50,180907	50,145865	50,11425	50,085589	50,059488	50,035623	50,01372	49,993549	49,974914	49,957646	49,941602	22,06468
%A: 20 %B: 50 %C: 10 %D: 20	47,942755	47,892066	47,846369	47,804963	47,767273	47,732821	47,70121	47,672101	47,645211	47,620295	47,597144	47,575578	23,141556
%A: 20 %B: 50 %C: 20 %D: 10	47,192569	47,140946	47,094379	47,052163	47,013716	46,978556	46,946281	46,91655	46,889073	46,863606	46,839934	46,817876	24,712106
%A: 30 %B: 30 %C: 10 %D: 30	49,758768	49,701382	49,649593	49,602621	49,559827	49,520678	49,484728	49,451601	49,420977	49,392584	49,366187	49,341582	20,547081
%A: 40 %B: 30 %C: 20 %D: 10	49,372572	49,320785	49,2741	49,2318	49,193298	49,158105	49,125814	49,096081	49,068614	49,043165	49,019519	48,997492	22,699054
%A: 60 %B: 10 %C: 10 %D: 20	51,449688	51,430606	51,413816	51,398951	51,385713	51,373861	51,363199	51,353565	51,344824	51,336862	51,329585	51,322912	20,327898
%A: 10 %B: 20 %C: 20 %D: 50	48,63007	48,584719	48,543901	48,506973	48,473407	48,442766	48,414685	48,388858	48,365025	48,342964	48,322486	48,303427	22,417728

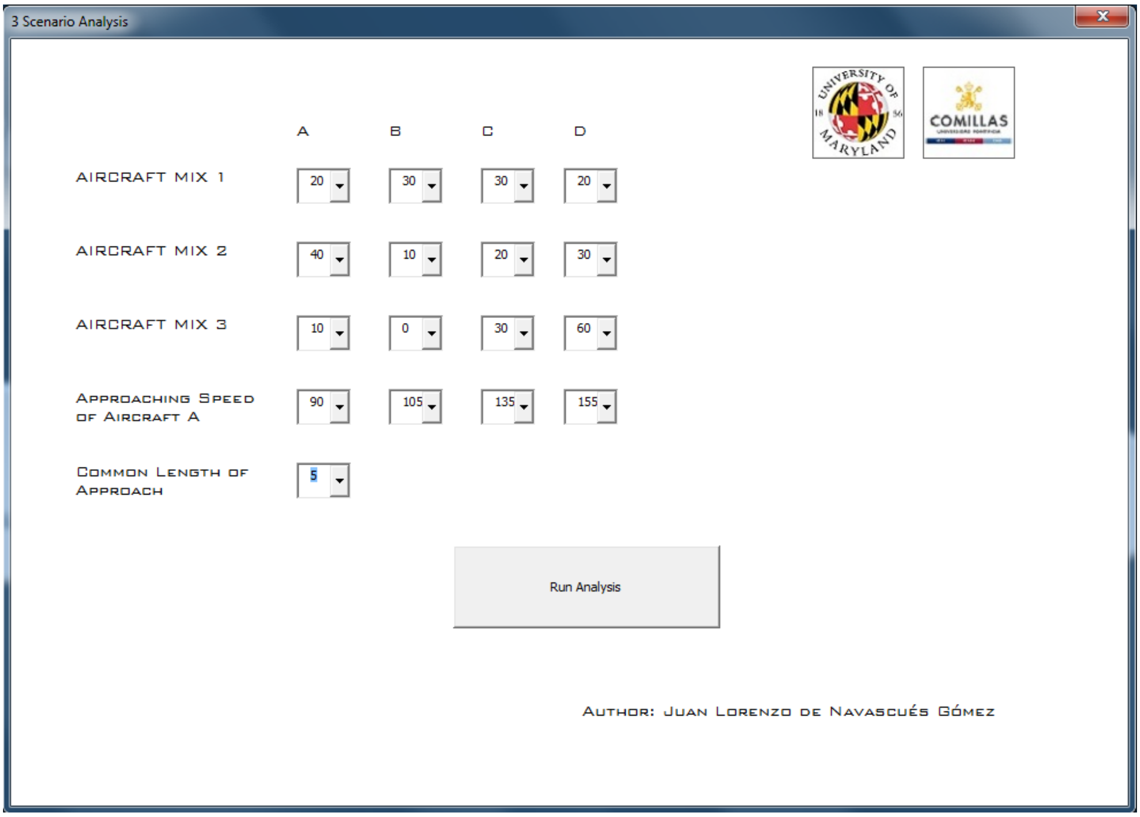




Gap for a takeoff between two consecutive landings [seconds]				
TRAILING AIRCRAFT	LEADING AIRCRAFT			
	A	B	C	D
A	-22,92	7,94	111,25	184,93
B	-26,10	-27,00	66,78	130,93
C	-30,25	-31,15	-19,07	46,47
D	-31,69	-32,59	-21,93	-1,27



3 Specific Case Analysis



Average Headway Aircraft Mix	Cycle Size 6	7	8	9	10	11	12	13	14	15	16	17
%A: 20 %B: 30 %C: 30 %D: 20	119,28	114,85	111,53	108,95	106,89	105,20	103,79	102,60	101,57	100,69	99,91	99,23
%A: 40 %B: 10 %C: 20 %D: 30	123,43	119,00	115,68	113,10	111,03	109,34	107,94	106,74	105,72	104,84	104,06	103,38
%A: 10 %B: 0 %C: 30 %D: 60	120,72845	116,30181	112,98182	110,39961	108,33385	106,64367	105,23519	104,0434	103,02187	102,13654	101,36188	100,67835

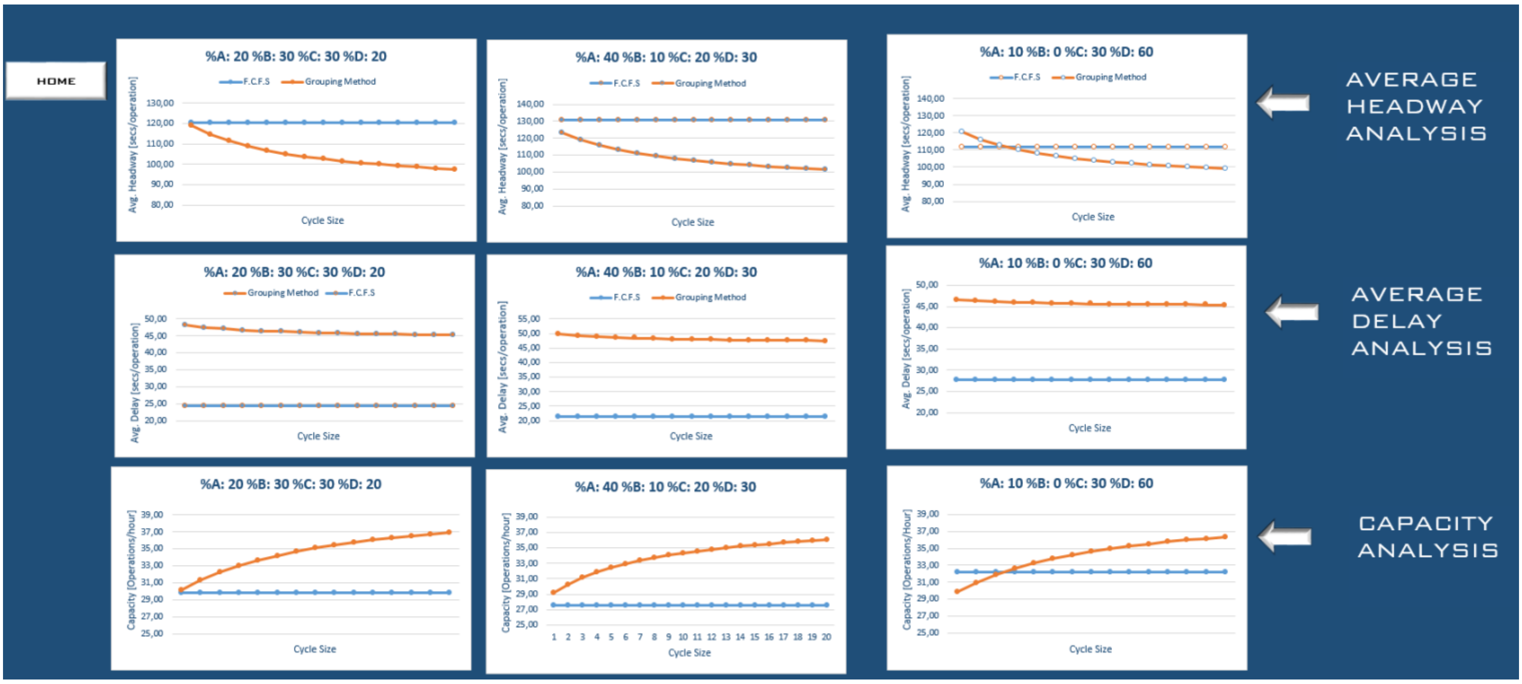
Average Headway Aircraft Mix	18	19	20	21	22	23	24	25	26	27	28	29	30	Mixed Arrivals
%A: 20 %B: 30 %C: 30 %D: 20	98,62	98,08	97,59	97,15	96,75	96,38	96,04	95,73	95,45	95,18	94,93	94,71	94,49	120,67
%A: 40 %B: 10 %C: 20 %D: 30	102,77	102,23	101,74	101,30	100,89	100,53	100,19	99,88	99,59	99,33	99,08	98,85	98,64	131,00
%A: 10 %B: 0 %C: 30 %D: 60	100,07077	99,527151	99,03789	98,595226	98,192804	97,825375	97,488565	97,178699	96,89267	96,627828	96,381903	96,152939	95,939239	111,8

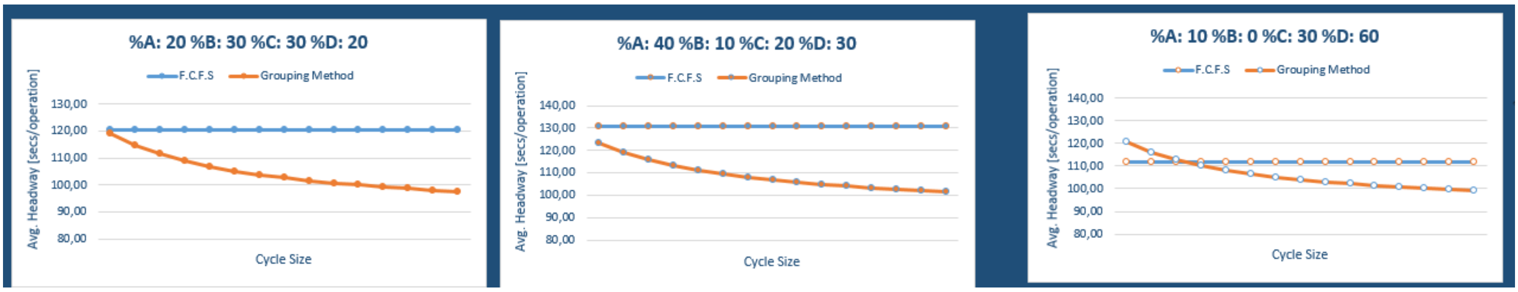
Capacity Aircraft Mix	Cycle Size 6	7	8	9	10	11	12	13	14	15	16	17
%A: 20 %B: 30 %C: 30 %D: 20	30,18	31,34	32,28	33,04	33,68	34,22	34,69	35,09	35,44	35,75	36,03	36,28
%A: 40 %B: 10 %C: 20 %D: 30	29,17	30,25	31,12	31,83	32,42	32,92	33,35	33,73	34,05	34,34	34,59	34,82
%A: 10 %B: 0 %C: 30 %D: 60	29,818986	30,953947	31,863533	32,60881	33,230612	33,757277	34,209088	34,600944	34,944036	35,246934	35,516311	35,757438

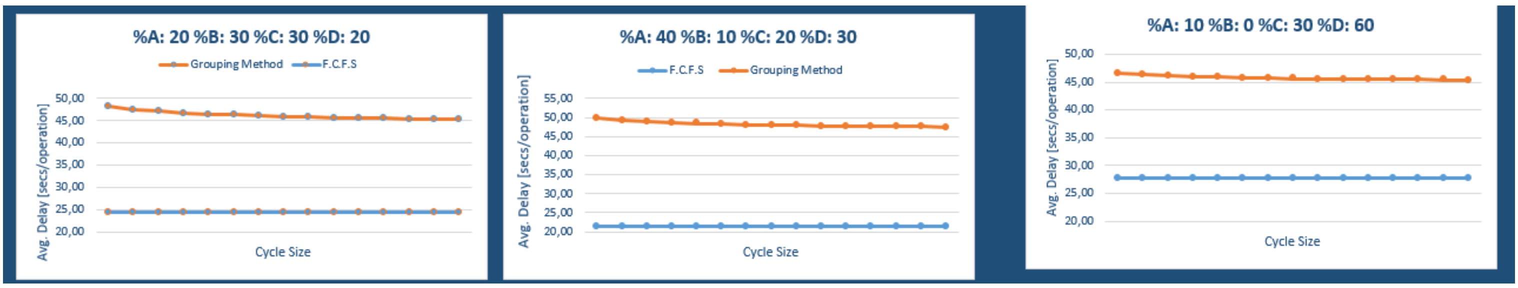
Capacity Aircraft Mix	18	19	20	21	22	23	24	25	26	27	28	29	30	FCFS
%A: 20 %B: 30 %C: 30 %D: 20	36,50	36,70	36,89	37,06	37,21	37,35	37,48	37,61	37,72	37,82	37,92	38,01	38,10	29,83
%A: 40 %B: 10 %C: 20 %D: 30	35,03	35,22	35,38	35,54	35,68	35,81	35,93	36,04	36,15	36,24	36,33	36,42	36,50	27,48
%A: 10 %B: 0 %C: 30 %D: 60	35,974539	36,171034	36,349724	36,512924	36,662565	36,800268	36,927408	37,045155	37,154513	37,256348	37,35141	37,440353	37,52375	32,200358

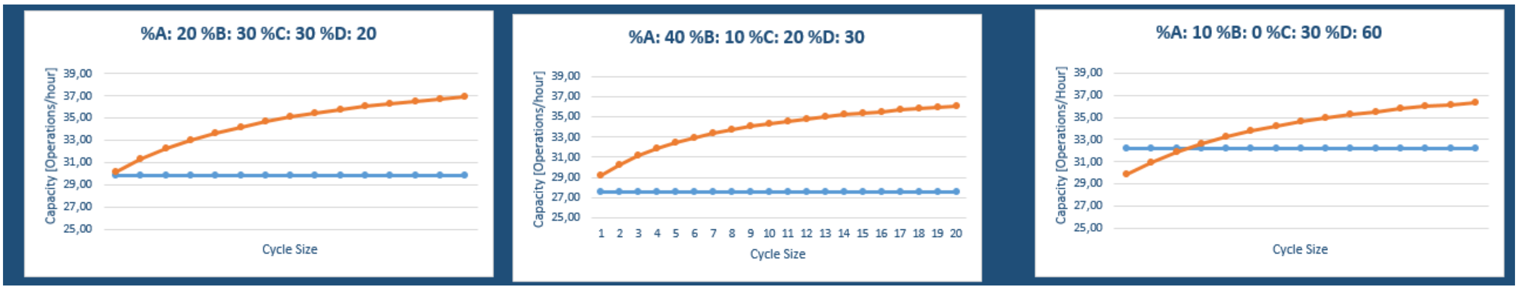
Average Delay Aircraft Mix	Cycle Size 6	7	8	9	10	11	12	13	14	15	16	17
%A: 20 %B: 30 %C: 30 %D: 20	48,16	47,58	47,14	46,79	46,52	46,30	46,11	45,95	45,82	45,70	45,60	45,50
%A: 40 %B: 10 %C: 20 %D: 30	49,86	49,36	48,99	48,71	48,49	48,31	48,16	48,04	47,93	47,84	47,76	47,69
%A: 10 %B: 0 %C: 30 %D: 60	46,704755	46,391871	46,172395	46,011533	45,8895	45,794317	45,71836	45,656575	45,605495	45,562669	45,526327	45,495155

Average Delay Aircraft Mix	18	19	20	21	22	23	24	25	26	27	28	29	30	FCFS
%A: 20 %B: 30 %C: 30 %D: 20	45,42	45,35	45,29	45,23	45,18	45,13	45,08	45,04	45,00	44,97	44,94	44,91	44,88	24,41
%A: 40 %B: 10 %C: 20 %D: 30	47,63	47,58	47,53	47,49	47,45	47,41	47,38	47,35	47,32	47,29	47,27	47,25	47,23	21,42
%A: 10 %B: 0 %C: 30 %D: 60	45,468167	45,444604	45,423878	45,405523	45,389168	45,374516	45,361322	45,349386	45,338543	45,328652	45,319599	45,311283	45,303622	27,735742


HOME
%A: 20 %B: 30 %C: 30 %D: 20
%A: 40 %B: 10 %C: 20 %D: 30
%A: 10 %B: 0 %C: 30 %D: 60
F.C.F.S
Grouping Method
Avg. Headway [secs/operation]
Avg. Delay [secs/operation]
Capacity [Operations/hour]
Cycle Size
AVERAGE HEADWAY ANALYSIS
AVERAGE DELAY ANALYSIS
CAPACITY ANALYSIS


%A: 20 %B: 30 %C: 30 %D: 20
%A: 40 %B: 10 %C: 20 %D: 30
%A: 10 %B: 0 %C: 30 %D: 60
F.C.F.S
Grouping Method
Avg. Headway [secs/operation]
Cycle Size


%A: 20 %B: 30 %C: 30 %D: 20
%A: 40 %B: 10 %C: 20 %D: 30
%A: 10 %B: 0 %C: 30 %D: 60
Grouping Method
F.C.F.S
Avg. Delay [secs/operation]
Cycle Size


%A: 20 %B: 30 %C: 30 %D: 20
%A: 40 %B: 10 %C: 20 %D: 30
%A: 10 %B: 0 %C: 30 %D: 60
Capacity [Operations/hour]
Cycle Size