A static algorithm to solve the air traffic sequencing problem

E. ROMANO, L.C. SANTILLO, P. ZOPPOLI
Dipartimento di Ingegneria dei Materiali e della Produzione
Università degli Studi di Napoli "Federico II"
p.le Tecchio, 80 - 80125 Napoli
ITALY
elromano@unina.it, santillo@unina.it, pasquale.zoppoli@unina.it http://www.impianti.unina.it

Abstract: - This work contributes to the development of microscopic traffic performance models in the airport. It enhances the existing models and develops new ones. An important contribution of this research is the empirical work, i.e. estimating models using statistically rigorous methods and microscopic data collected from real traffic. With the ever increasing congestion at airports around the world, studies into ways of maximizing infrastructures capacity and minimizing delay costs while meeting the goals of the airlines are necessary. The methodology applied for the calculation of runway capacity start from the traffic data elaboration of the Naples International Airport: we have been determined this aim from the airline pattern in the above airport. The hourly capacity is calculated as the inverse of the headway of consecutive aircraft operation; this is drawn with an average of the time headway in the "critical periods". The determination of the "capacity periods" it happens in three phases: in the first one we are drawn by the sample the stationary periods; in the second we are considered, of these, only those with the lowest averages time headway, these are called "critical" periods; subsequently we are examined only that (critical periods) had time length less than the 60 minutes and that have an average of time headway that it is almost attested around to a constant value. The stationary periods, as it says the same definition, are characterized by the relatives constant time headway, in other words there aren't meaningful phenomenon of increase or diminution of the traffic flow. The critical periods are static periods that are found on the traffic flow curve defined "critic", this curve we have obtained to envelop some values that mark the lower limit of the diagram defined time length vs. averages of the static periods. Defined the critical periods we have been determined the experimental headway curves and we compared with those theoretical. Of such experimental curves we have been considered the characteristics values: the average and the standard deviation. In this way we have determined a matrix of the average time headway both for operations flight that for type of airplane. The following step has been that to define and to implement the analytical model. We suggest a mathematic algorithm that is able to optimize, a posteriori, the flight operation under the delay restraint. The algorithm determines the best sequence of aircrafts that minimizes the delays and it maximizes the runway capacity. The proposed methodology, even if determine an evident improvement of the runway capacity, in the respect of thresholds of acceptable average delays (constrain), represents an initial methodological phase that will desirably conclude in the determination of a "dynamic" model, that is able to assist the inspectors' job in way real-time, assigning, opportunely, an excellent sequence of the successions of flight operations.

Key-Words: - scheduling, simulation, airport capacity, aircraft sequencing

1 Introduction

Increased air travel has added growing numbers of travellers and flights to an already congested system. The result is an almost inevitable rise in air traffic delay.

A major goal of air traffic management is to strategically control the flow of traffic so that the demand at an airport meets but does not exceed the operational capacity in a dynamic environment. To achieve this goal in real-time, there are currently two practical ways to carry out online capacity management based on updated environment information. One is to adjust in real-time the capacity allocation for current time interval based on the plan which has been made in advance. The other is to re-allocate capacities for the rest of the operating day in a globally optimizing way.

The determination of an airport capacity is complex. Airport capacity depends on many factors, such as meteorological conditions, runway configurations, arrival departure ratio, and fleet (aircraft type) mix. Furthermore, the practical capacity for the purposes of strategic traffic management may be affected by airspace factors (e.g., arrival fix loading, sector loading) as well as human factors (e.g., controller workload). The vast majority of publications on analysis and optimization of air traffic flow management treats the airport capacities as given, constant parameters. Usually, the airport capacity is defined by two constants: one for arrival capacity and another for departure capacity. The constants can vary for different weather conditions and runway configurations, but they remain constant throughout the time those conditions exist. The engineered performance standards (EPS) developed by the FAA give more realistic information on airport capacities. The EPS values vary not only by runway configuration and weather, but also by arrival departure ratio. Three operating conditions are generally given: departure priority (75% or more departures), equal priority (50% arrivals and 50% departures), and arrival priority (75% or more arrivals). For some airports the EPS show only one pair of arrival and departure capacity values for each runway configuration. However, even in the best cases, the EPS data do not cover the entire range of arrival departure ratios.

The most complete information on airport capacities under various arrival/departure ratios can be represented by a functional relationship between arrival and departure capacities. In one of these studies, the analytical model called the FAA Airfield Capacity Model, was developed. This model is capable of determining the relationship between arrival and departure capacities. The MITRE Corporation appears to be the first to apply this relationship in the NASPAC (National Airspace System Performance Analysis Capability) simulation model, where arrival and departure slots can be assigned in response to peak demands. In this paper, a similar representation of airport capacity is used to estimate the capacity and to formulate a new approach to the operational optimization of airport capacity.

The principal scope of this paper is to examine how much, given realistic constraints, better sequencing in the terminal area might actually improve operations. After a state of art of scientific literature, it is reported a brief description of the setting for this study, Naples International Airport, and with some basic definition of Air Traffic Control conventions and terminology. Then it describes, in the first, the data used in the study and the statistical model implemented to determine the better sequencing between two successive typology of aircraft and operation (landing or take – off) and the model that determine the Aircraft Sequencing Problem. Finally it describes the model for the terminal area, the sequencing algorithms developed, and compare the results to those actually achieved by controllers.

2 Definitions and background

International air transport is the fastest growing segment of transportation. This can be partially attributed to a combination of market trends and institutional reforms combined with rising incomes and increased leisure time. Air passenger traffic since 1960 has grown worldwide at an average yearly rate of 9 percent with freight and mail traffic growing at 11 percent and 7 percent respectively. In 1995, some 1.3 billion passengers were carried by the world’s airlines. For European air passenger traffic growth, the projected annual growth rate is 5.2 percent between 1993 and 2000, 4.2 percent between 2000 and 2005, and 3.8 percent between 2005 and 2010 (ATAG, 1996). This growth is graphically displayed for the top 16 European airports analyzed in this study (representing 78 percent of total European passenger transport). In addition to passenger transport, air transportation has 3 become an important form of freight transport. Freight traffic is predicted to grow at 30 percent over the same time. The International Civil Aviation Organization (ICAO) estimates that over 30 percent of world trade by value is transported by air with forecasts of it rising another 400 percent by 2015. This continued rise in air transport activity has placed enormous pressure on the finite capacity of the air transportation system. In particular, the effect of reaching capacity limits has caused the number and length of air transportation delays to increase. This could affect future economic growth, especially for export-oriented economies such as Germany (Huttig, Busch, & Gronak, 1994). Therefore, understanding delays and their relationship to capacity becomes very important (Reynolds- Feighan and Button, 1999). There are a number of high resolution models available that will assist in the understanding of the factors involved with capacity and delays. These models provide a detailed analysis, but require significant amounts of data that are sometimes difficult to obtain. Learning to use these models takes considerable time and effort limiting their use to specialized individuals.

The intensive analytical studies on airport operational capacities began in the late 1950’s. Since then, a large number of publications have addressed various aspects of the studies. Airport capacity is defined as the maximum number of operations (arrivals and departures) that can be performed during a fixed time interval (e.g., 15 minutes or one hour) at a given airport under given conditions such as runway configuration, and weather conditions. It is calculated as the reciprocal of the mean permissible interoperation time.

The existing analytical methods (see R. M. Harris - 1972, Kanafani et al. - 1974, G. F. Newell - 1979, and W. J. Swedish - 1981) provide the estimation of the mean inter-operation times by taking into account the uncertainty in the time of aircraft appearance at particular points at different stages of arrival and departure, stochastic variability in speed, differences in runway occupancy times, as well as the uncertainty in aircraft fleet mix. By making assumptions about the distribution functions of the random variables, one can estimate minimum interoperation times, which provide a given probability of not violating safe separation distance requirements. The minimum inter-operation times are in turn used to calculate the airport capacities. The numerical results substantially depend on the a priori suppositions about probability distributions and their parameters. The reliability of the capacity estimates depends on the reliability of the a priori information (which is often not very good). A way to get more reliable, realistic estimates is to combine analytical and empirical methods. Empirical data, such as historical counts of arrivals and departures at the airport, makes it possible to correct the analytical models and their parameters. It has been established that arrival and departure capacities are connected with each other through a convex, nonlinear functional relationship (E. P. Gilbo, 1993). The existence of the relationship reflects the fact that the arrival and departure capacities are interdependent. A specific relationship between the arrival capacity c, and departure capacity $cd = \varphi(ca)$ depends on various factors such as runway configuration, weather conditions, aircraft fleet mix, runway operating strategy, and characteristics of the air traffic control system. Geometrically, the relationship can be shown on an arrival capacity/departure capacity plane by a capacity curve, illustrated in Figure 1, which represents a set of capacity values that reflect the operational capabilities of the airport under certain conditions. To make the relationship specific for an airport requires a complex approach that includes a combination of mathematical modelling using empirical data, and validation of the results using the expertise of practicing traffic managers and controllers.

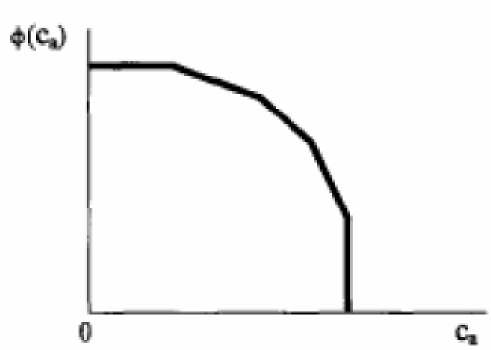


Fig.1: Airport arrival - departure capacity curve

It is useful to classify capacity and delay models according to three aspects: *level of detail*; *methodology*; and *coverage*.

With respect to the first, we classify models into *macroscopic*, *mesoscopic and microscopic,* corresponding respectively to a low, intermediate and high level of detail. While the boundaries among these three classes are not particularly sharp (e.g., the same model might be characterized as “low-level-of-detail” by some or “intermediate-level” by others) it is nonetheless very useful to classify models along these lines. Macroscopic models omit a great deal of detail, since their objective is to obtain approximate answers with emphasis on assessing the *relative performance* of a wide range of alternatives. For example, air traffic demand may be described in such a model by simply an hourly rate of arrivals at an element (airport, sector, etc.) of the ATM system and a simple probabilistic description of how these arrivals occur over time (e.g., “Poisson arrivals”). These models are used primarily for policy analysis, strategy development and cost-benefit evaluation. Ideally they should be fast, in terms of both input preparation and execution times, so they can be used to explore a large number of “scenarios”. Mesoscopic models, while more detailed than macroscopic ones, are still rather strategic in nature. For example, a mesoscopic model may be concerned with aggregate flows per unit of time through one or more elements of the ATM system (e.g., for flow management purposes) without being concerned with how these flows are handled, as long as the flows remain below some pre-defined “capacities”. Finally, microscopic models are designed to deal with more tactical issues. Typically, such models represent aircraft on an individual basis and move them through the ATM elements under study by taking into consideration each aircraft’s performance characteristics. Such detailed features as conflict resolution, airport taxiway and gate selection, pushback maneuvering, etc., are generally included only in microscopic models.

With respect to methodology, we distinguish between *analytical* and *simulation* models. The former are abstract, necessarily simplified mathematical representations of airport and airspace operations. By manipulating these 5 expressions (either in closed form or numerically) analytical models derive estimates of capacity and delays in airspace and/or airports. In contrast, the classical approach of simulation modelling is to create objects (typically aircraft) which move through the airspace segments and airports of interest. By observing the flows of such objects past specific locations (e.g., the threshold of a runway or an en route waypoint) and the amount of time it takes for aircraft to move between such points, the simulation models compute appropriate measures of capacity and delay. There is a strong correlation in practice between methodology and level of detail: specifically, analytical models tend to be mostly macroscopic in nature, whereas most simulations are mesoscopic or microscopic. Models (whether analytical or simulations) can be further distinguished in terms of methodology, according to whether or not they are (a) *dynamic* and (b) *stochastic*. Dynamic models will accept input parameters which are time-dependent and will capture the fluctuations over time in the performance metrics of airports and/or airspace traffic. Similarly, stochastic models will accept input parameters which are specified probabilistically (i.e., are random variables) and will capture the impacts of uncertainty on the performance metrics of airport and/or airspace traffic. Stochastic *simulation* models are often referred to as *Monte Carlo* simulations.

Finally, with respect to coverage, we classify capacity and delay models according to whether they encompass operations of the following elements of airports and airspace: (1) aprons and taxiways; (2) runways and final approaches; (3) terminal area airspace; and (4) en route airspace. Combinations of more than one of these components are, of course, possible so that some models may be able to examine an airport in its entirety, or even a national or regional system of airports, terminal areas and en route sectors.

Table 1: Classification of Analytical and Fast-Time Simulation Models of Capacity and Delay

	SCOPE OF METHOD			
LEVEL OF DETAIL	**Aprons and taxiways**	**Runways and final approach**	**Terminal area airspace**	**En route airspace**
Macroscopic (policy analysis, cost-benefit analysis)		LMI FAA DELAYS AND		ASIM SDAT DORATSK
Mesoscopic (traffic flow analysis, cost – benefit analysis)		NASPAC TMAC FLOWSIM ASCENT		
Microscopic (detailed analysis and preliminary design)	TAAM SIMMOD			
Same	The Airport Machine HERMES		RAMS	

Existing macroscopic models concentrate on runway capacities and associated delays or on en route sector operations. General purpose, macroscopic models of taxiway/apron operations and of terminal airspace operations do not exist, because such models need to be location-specific. Of the runway/final approach models listed in Table 1., the top two estimate capacity, while DELAYS and AND estimate airport-related delays. The LMI Runway Capacity Model is still under development and, at this point, covers only single-runway airports in general form. For any given aircraft mix and set of separation requirements, it computes (1) the all-departures capacity of a runway, (2) the all-arrivals capacity, (3) the number of "free" departures that can be performed without reducing the all-arrivals capacity and (4) the capacity of the runway if a departure is always inserted between two arrivals, so that arrivals alternate with departures on the runway. The capacity of the runway for any other mix of arrivals and departures and any other sequencing of arrivals and departures can then be computed approximately by utilizing the four estimates above. (For configurations involving the simultaneous use of more than one runway, the model has to be extended on an ad hoc basis for each airport.)

The FAA Airfield Capacity Model computes the capacity of 14 different common runway configurations, ranging from one to four simultaneously active runways. Its logic differs in several significant respects from that of the LMI Model. DELAYS views the runway system of an airport as a queuing system whose "customers" are aircraft demanding to land or take-off and whose capacity is equal to the arrival, departure or total capacity of the runway system, depending, respectively, on whether one is interested in delays to arrivals, to departures or to the "average operation". The model is based on a fast approximation scheme for solving the differential equations that describe a quite general dynamic queuing system.

The Approximate Network Delays (AND) model is a complex extension of DELAYS that considers a network of airports, instead of a single airport, and computes how delays in any part of that network would "spread", due to disruption of airline schedules, to the rest of the network. The model's intent is to help evaluate the system-wide implications (on a national or regional scale) of changes in (i) the capacity of one or more airports and/or (ii) the amount or geographical distribution or temporal distribution of airport demand. Of the en route macroscopic models, ASIM and DORATASK are fast approximate simulations for computing, respectively, the expected number of aircraft conflicts and the expected controller workload, in a single sector or in a set of sectors, that would result from any given pattern of traffic flows along a structured set of airways. SDAT is an analytical model that, for some given pattern of traffic flows, would support the design of en route sectors with the objective of minimizing sector workload resulting from the routine handling of traffic, as well as the resolution of conflicts. Thus, the principal focus of all three of these models is on controller workload and on aircraft conflicts (see also the next Section). They are related, however, to capacity and delay in the sense that en route sector capacity is largely determined by controller workload, which, in turn, is influenced heavily by the potential number of conflicts that a controller may be called on to resolve.

The four mesoscopic models listed in Table 1. are all recent (the oldest, NASPAC, was initially developed in 1988). NASPAC was initially designed as a national- or regional-scale, macroscopic simulation whose objective, like that of AND, was to study a network of airports and compute how delays in any part of that network would "spread". However, many details were subsequently added to NASPAC, so that today it is primarily used to deal with traffic flow management (TFM) issues, rather than predictions of capacity and delay. The focus of the other three models listed, FLOWSIM, TMAC and ASCENT is also on TFM. TMAC, a model under continuing development at MITRE) has also been used recently in connection with the preliminary evaluation of some of the benefits that may be obtained from the Free Flight concept. Of the three models, FLOWSIM is the most mature, while new capabilities are currently being added to the other two, especially the ASCENT model of the C.S. Draper Laboratory, which is being expanded to cover both strategic and tactical aspects of TFM.

An important distinction in the case of microscopic models is between node-link and 3-dimensional (3D) models. Node-link models discretize airports and airspace into a number of nodes and links.

Aircraft move from node to node along the links and conflicts occur when more than one aircraft try to move to a single node. These conflicts are resolved by delaying one or more of the aircraft at a node.

By recording the amount of delay incurred at each node by each aircraft, the model compiles the requisite aggregate and distributive delay statistics. SIMMOD and The Airport Machine are node-link microscopic models, as are ASIM and FLOWSIM among the macroscopic and mesoscopic models, respectively. 3D models allow aircraft to fly arbitrary three-dimensional routes. (When simulating airport surface traffic operations, these are, of course reduced to 2D models.) In some 3D models, aircraft follow specified flight plans exactly; in others, aircraft dynamics equations are used to simulate aircraft performance. Flight paths may thus deviate from planned flight plans. RAMS, TAAM and HERMES are microscopic 3D models —and so are TMAC and ASCENT among mesoscopic models.

Most of the models in the microscopic category are well-known. SIMMOD, TAAM and The Airport Machine have been used in numerous airspace and/or airport studies in many parts of the world. The former is a model developed with support from the FAA and is available at little direct cost, while the latter two are proprietary and carry significant license fees. SIMMOD and TAAM cover both airspace and airport operations, while The Airport Machine is limited to airport operations only. RAMS is an airspace operations modeler, developed recently by Eurocontrol, which also controls its availability.

The least-known model, HERMES, has been developed by CAA/NATS in the UK and its use is currently limited to simulating in detail operations at London's Heathrow and Gatwick Airports.

3 Traffic data analysis

The Naples-Capodichino airport is located in the north east of the city. The airport is at a height of about 90 metres above sea level and has an annual average temperature of 19°C. The airfield is at single runway, RWY 06-24, inclined of 57° as to geographic north. It is 2650 metres long, 45 metres wide and 0,89% inclined. The runway has a threshold moved for the landing of 405 metres on the head 06 and 200 metres on the head 24, to provide the necessary distance on these obstacles.

There is a taxiway that places side by side the runway for all of its length. To link runway and taxiway there are 9 connections denominated, beginning from the Apron (near the heading of the runway 06) toward the threshold 24, from code A to G; on the North side of this last there are other two links, H and L. To allow the parking of the aircrafts there is a Apron divided in 3 parts (WA - west apron, CA - central apron, EA - east apron); there is a zone reserved to the military traffic and positioned in proximity of threshold 06; on the same area is positioned stands for also aircrafts of the General Aviation. The North side of the airport has served from a series of small links that connects 8 platforms dedicate both for the long term aircraft parking and for the aircraft maintenance parking.

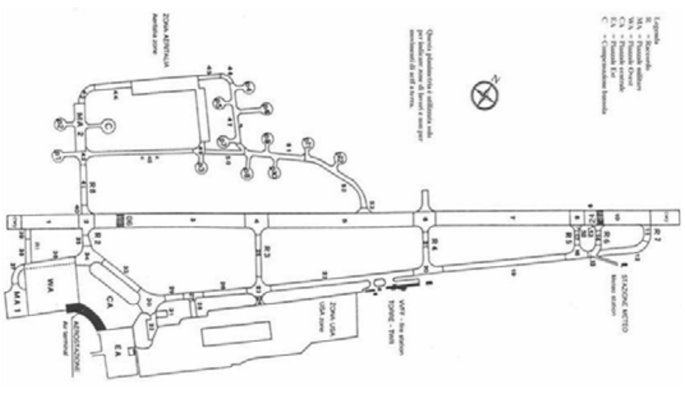


Fig. 2: Layout of Naples International Airport

The CTR (Control Traffic Region) for Naples is a region of airspace extending up to about 60 nm around the airport and 10.000 feet above it. Towers control the movement of aircraft in this area. Thus when an aircraft departs it is under the control of the tower until takeoff and then is handed over the other control. The CTR contain SIDS' (Standard Instrument Departure) and STARS' (Standard Terminal Arrival Route) and instrumental procedures (ILS).

The airplane volume around the Naples airport includes 11 instrumental approach routes and 8 departure routes that are under the direct control of the Naples APP centre and other VFR routes managed from the airport control tower.

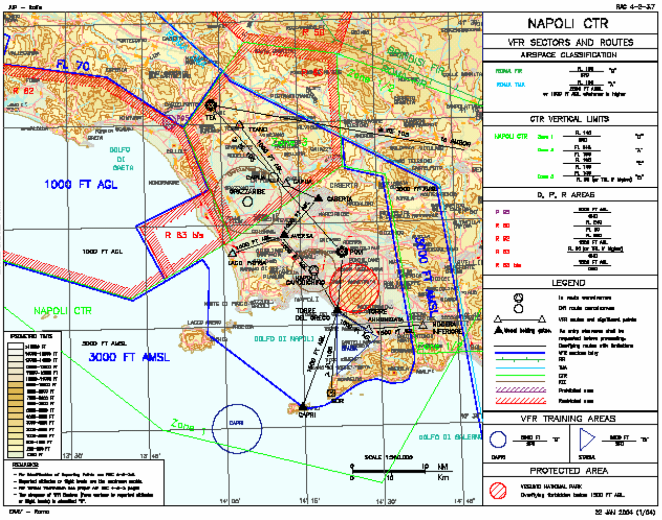


Fig. 3: Airspace around Capodichino Airport.

From the historical data relived from 1985 to 2003, source GESAC – BAA (society that manage Handling Services in the Naples Airport) has be seen that the passenger volume growing and may be approximate well from a linear type function. You foresees therefore that for the year 2020 the airport will have an appraisable load of annual passengers in around 9.000.000. The present traffic on the airport can be distributed in: Italian Business, foreign business, Italian leisure, foreign leisure.

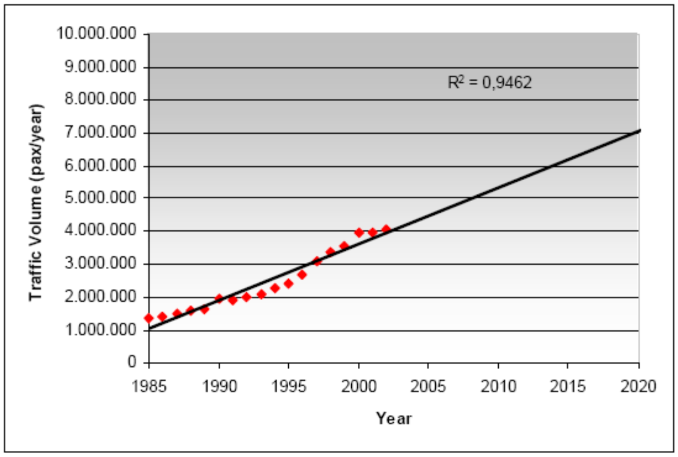


Fig. 4: Traffic Volume Forecast

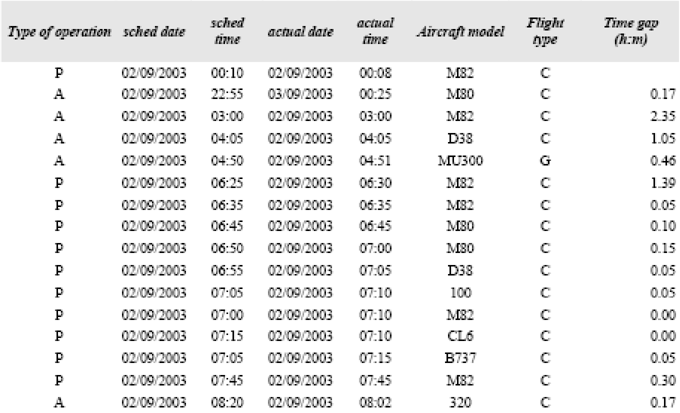
To determine the month of greater traffic it is necessary to analyze the subdivision of the seasonal traffic. Such division shows that the month of greater load is September. It may be assert more particularly that in the months between June and July the traffic flow increase, because of the traffic leisure that it has the tendency to grow, while in the August it is possible to see a light decrease in relation to decrease of business demand. From the data analyzed may be showed that the principal trip motivation is the tourism (69%) while the subdivision for nationality underlines as the airport is used for the most greater part by Italian travellers (81%). The data are synthesized in the following table:

Table 2: Traffic month distribution

PASSENGERS	*MONTH*
214.472	February
271.622	March
348.606	April
405.073	May
418.797	June
422.929	July
413.687	August
441.091	September
384.796	October
384.796	November
234.136	December
239.635	January
4.179.640	**Total traffic in the Year**

Then in the next phase of study it has been determined the collection of the real and official schedules of landing and take-off of the aircrafts furnished by the ENAC. Such data are necessary to determine the succession and the relative time distance among flight operations.

Table 3: Scheduled flight time typology (ENAC)

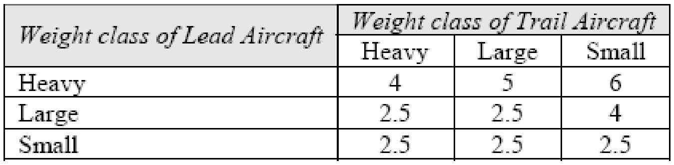


Type of operation	*sched date*	*sched time*	*actual date*	*actual time*	*Aircraft model*	*Flight type*	*Time gap (h:m)*
P	02/09/2003	00:10	02/09/2003	00:08	M82	C	
A	02/09/2003	22:55	03/09/2003	00:25	M80	C	0.17
A	02/09/2003	03:00	02/09/2003	03:00	M82	C	2.35
A	02/09/2003	04:05	02/09/2003	04:05	D38	C	1.05
A	02/09/2003	04:50	02/09/2003	04:51	MU300	G	0.46
P	02/09/2003	06:25	02/09/2003	06:30	M82	C	1.39
P	02/09/2003	06:35	02/09/2003	06:35	M82	C	0.05
P	02/09/2003	06:45	02/09/2003	06:45	M80	C	0.10
P	02/09/2003	06:50	02/09/2003	07:00	M80	C	0.15
P	02/09/2003	06:55	02/09/2003	07:05	D38	C	0.05
P	02/09/2003	07:05	02/09/2003	07:10	100	C	0.05
P	02/09/2003	07:00	02/09/2003	07:10	M82	C	0.00
P	02/09/2003	07:15	02/09/2003	07:10	CL6	C	0.00
P	02/09/2003	07:05	02/09/2003	07:15	B737	C	0.05
P	02/09/2003	07:45	02/09/2003	07:45	M82	C	0.30
A	02/09/2003	08:20	02/09/2003	08:02	320	C	0.17

4 A statistical model to determine time interval among aircraft operations

One key factor that can affect the distance separation between aircraft is the minimum in – trail separation requirement that has been imposed by Federal Aviation Administration (FAA) to guard against dangers from collision and wake – vortex turbulence. To lessen collision risk, a minimum base separation of 2.5 nm is usually applied between any two aircraft. There is then an additional wake – vortex separation depending on the weights of the lead and trail aircraft. The FAA has defined three classes of planes in terms of their weight: Heavy, Large, and Small. Heavy aircraft comprises the B747, B767, A300, etc. The large aircraft include a wide range, from a turboprop like ATR42, to the B757 and DC9. Small aircraft consist primarily of small piston engine aircraft and the smallest turboprops like Beech 99. Based on this three weight classes, the FAA has established standards for the minimum separation between successive aircraft in a flight path.

Table 4: FAA separation standards (nm)



Weight class of Lead Aircraft	*Weight class of Trail Aircraft*		
	Heavy	Large	Small
Heavy	4	5	6
Large	2.5	2.5	4
Small	2.5	2.5	2.5

These separation standards are mandatory in IMC; when they are in effect, aircraft are deemed to be flying under Instrument Flying Rules (IFR). In good VMC the tower may offer aircraft the opportunity to maintain visual separation from each other. Beginning from the data provided by ENAC – Naples DCA the distance separation has been divided according to the weight class of the airplane that trailing and that follows. This has produced, 14 therefore, the following classes of survey:

LL LM LH ML MM MH HL HM HH

where:
L is Light;
M is Medium;
H is Heavy.

The sequence LM foresees therefore a type L aircraft followed by one type M.

Moreover it is necessary to relief the type of operation:

- take-off - take-off;
- take-off – landing;
- landing - take-off;
- landing – landing.

You can define then 36 different classes of survey. Nevertheless the configuration and the length of runway don’t allow takeoff, in particular load conditions, of class H aircraft. In fact may be show that the operation leaded with B747 and similar are a small number. For every class we will have to determine the distance separation. In the first step it is necessary to define the law of distance separation in the real case, also for the different classes of weight. Such function has been inferred through statistic analysis. The main question is that to establish when and in which condition the runway “works” near to capacity. In other words, before determining sample distributions of distance separation and relative characteristics (mean, standard deviation and percentiles), it is important to understand the data that it’s need to consider and what instead to discard. In other words the data of interest are those in heavy traffic periods. But the question is what’s period it may be considered as heavy traffic period? It may be answer defining, first, stationary (or regime) flow conditions. Such conditions are checked when the distance separation successions are characterized by constant value or oscillating around constant value. In these periods it is possible to check capacity condition. This to the purpose to discard measures that belong to trailing transitory periods or those following to the phase of regime. You notices, nevertheless, that the stationary condition of a phenomenon is necessary condition but not enough to define the system capacity. The stationary conditions are been defined correlating a linear sequence of increasing natural numbers with the values of distance separation determined by a sequence of operations. The correlation coefficient is defined, in this case

$$\rho_{n,d} = \frac{cov(N,D)}{\sigma_n \cdot \sigma_d} \tag{1}$$

where
N is the distribution of natural numbers and D the distance separation distribution;
cov(*N*,*D*) the covarianza of the two distributions;

σ_n , σ_d the standard deviations of the two distributions.

The limit values of the coefficient of linear correlation are -1 and +1. Insofar, if ideally the coefficient of correlation was equal to -1, a sequence with decreasing distance separation it would be had with, the inverse one would be verified in the case in which the coefficient was equal to + 1 (sequence of operations with increasing gap times). For these considerations, the flow distribution (landing or takeoff) can be defined under regime conditions if the correlation coefficient assumes values near to the zero. In fact, such condition of the coefficient of correlation implicates that the two distributions are not correlated and therefore that the distance separation sequence is neither in increasing neither decreasing phase and then under stationary conditions.

This procedure has been conducted on every 30 day in September 2003 and may be synthesized in the following charts that brings in abscissa the periods length in the every 30 days related to the mean time duration of regime condition.

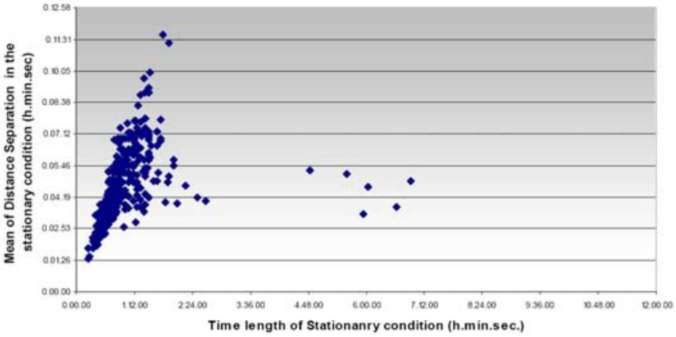


Fig. 5: Stationary period vs. mean of duration

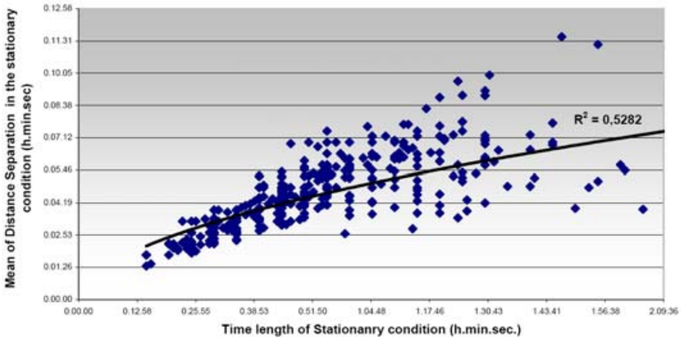


Fig. 6: Stationary period (two hour analysis) vs. mean of duration

The observations that derive from these diagrams are numerous. The most interesting, is the characteristic course of the observations "funnel-shaped". Therefore, for brief periods the means have limited variations, that increase with to increase stationary periods. This involves that the methodology until here exposed can result particularly effective, to the goals of the determination of the conditions of capacity, for brief periods while for periods of greater duration an analysis more detailed is necessary. The general shape of the means is increasing to increase time interval width. In other words, the distance separation between trailing and following aircrafts increase, as may be see from the curve that interpolate experimental data, if the duration of the stationary time period climbs. In first 17 approximation, this shape diagram increasing can explain at least two aspects, now known but ever shown: the first one is that the ATC controllers, to increase number of operations "stretch" a greater safety between two consecutive airplanes, because of to persist heavy traffic condition. The analysis above mentioned has concerned the individualization, inside the sample, the stationary period, or rather of temporal windows inside which the traffic flow demand can be considered under static conditions and not transitory. Nevertheless, for the individualization of the conditions of capacity it is necessary to individualize some periods in which the demand draws near to the capacity, or coincides with it. The periods examined in the sample of 31 days have means with varying shapes: to parity of period, in fact, experimental data shows both low and elevated means, as you can be inferred by the diagrams brought above. It is necessary therefore to extrapolate the periods that have let the lowest averages record. The values that have lowest mean, to parity of period, are been extrapolated. It is obtained the so called "critical cases". In the chart that follows the examined critical periods are showed with the relative day, the mean duration, the number of operations and the average distance separation among the operations.

Table 5: Critical periods with length lesser than 2 hours

AVERAGE DISTANCE SEPARATION	*TIME LENGTH*	*N. OF OPERATIONS*	*DAY*
0.03.25	0.41.00	12	01/09/2003
0.03.57	1.35.00	24	02/09/2003
0.02.06	0.21.00	10	03/09/2003
0.04.00	1.20.00	20	04/09/2003
0.01.54	0.16.00	10	05/09/2003
0.01.49	0.20.00	11	06/09/2003
0.04.12	0.42.00	10	07/09/2003
0.02.00	0.22.00	12	08/09/2003
0.03.17	0.45.00	14	09/09/2003
0.03.57	1.15.00	19	10/09/2003
0.03.36	0.50.00	15	11/09/2003
0.04.07	1.13.00	18	12/09/2003
0.02.24	0.23.00	10	13/09/2003
0.02.49	0.29.00	11	14/09/2003
0.02.30	0.25.00	10	15/09/2003
0.02.30	0.35.00	14	16/09/2003
0.03.45	0.58.00	16	17/09/2003
0.03.12	0.39.00	12	18/09/2003
0.02.34	0.33.00	14	19/09/2003
0.01.18	0.11.00	10	20/09/2003
0.06.34	1.44.00	16	21/09/2003
0.02.35	0.30.00	12	22/09/2003
0.05.00	0.57.00	12	23/09/2003
0.03.14	0.37.00	13	24/09/2003
0.02.50	0.32.00	12	25/09/2003
0.02.38	0.27.00	11	26/09/2003
0.02.18	0.46.00	20	27/09/2003
0.05.44	1.03.00	11	28/09/2003
0.02.24	0.24.00	10	29/09/2003

Such periods of heavy traffic are typically on work days in the morning between approximately 7 a.m. and 10 a.m., and in the afternoon between 5 p.m. and 8 p.m. In the week days such periods are typically recorded in the evenings, between approximately 5 p.m. and 9 p.m.

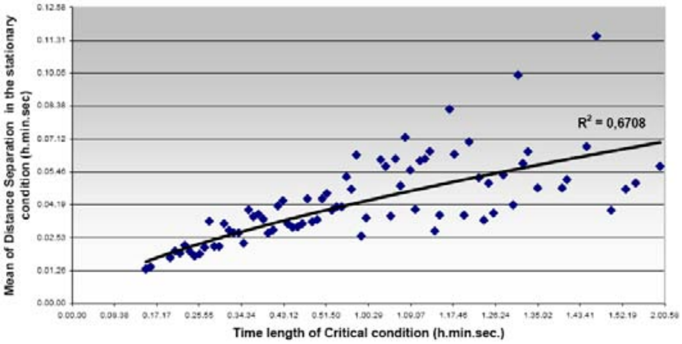


Fig. 7: Critical periods lesser than 2 hours

In the above figure it is represented the mean distance separation between two consecutive aircraft recorded in the critical periods and the relative curve that interpolate them. The interpolation of the points has been effected with a curve that have equation y = 0,0247x0,651 and degree of correlation R2 = 0.67. Every points brought in fig. 7 in the detail have been analyzed for determining the values for the 36 distance separation classes. In reality, because of the shortage of data inherent the class of weight H, has been possible to find a meaningful sample data only for 16 of the 36 classes, and precisely the LL, LM, ML and MM both for landings (A) and take-off (D). The distance separation are calculated in every period and, after separate them in classes, the 19 frequencies has been determined for every minute with the relative mean, finding that the most greater part of the observations they belong to the class MM, in every operational condition. Repeating the elaborations for every class the matrix of relative distance between classes of aircrafts in the different operations has been obtained.

Table 6: Time separation matrix deducted with statistical analysis (minutes)

	LL	*LM*	*ML*	*MM*
DD mean	1,20	2,19	3,09	2,62
AA mean	1,83	2,58	2,34	3,26
AD mean	1,33	2,97	2,33	2,98
DA mean	1,11	2,87	2,64	2,76

Such time separations are subject to a strong variability that can be attributed, among the other, to the different conditions in which an aircraft is found before landing or to take off and to the different degree of congestion of the structure. They appears, therefore, as of the random variable of which it is important to know the laws of probability. These last ones have been determined through the techniques of the statistic inference. As a random sample of the different aleatory variable in examination is tried to reconstruct its probability density function (pdf) drawing the distribution of the densities of frequency of it. Being aleatory continuous variable we proceeds to the collection of the respective experimental determinations in groups, according to the belonging to intervals of predetermined values. These intervals have been select of equal width, contiguous, closed to the right and in number neither too much great, to avoid to have empty intervals, neither too much small not to lose information around the form of the *pdf*. To choose the correct number of intervals in which to divide the range of observed values is made reference to the k number obtained by the following empirical formula:

$$k = 1 + 3{,}3\log_{10}(n)$$

$$\Delta x = \frac{x_{\max} - x_{\min}}{k} \quad (2)$$

where:

N is the sample dimension;
Δx is the width interval;
x_{max} [x_{min}] is maximum [minimum] value in the aleatory distribution. The number of values n_i in every interval divided up n and the width of the interval determined the density of frequency f_i that insists on the i generic interval.
For the f_i the followings relationships are equal to:

$$f_i = \frac{n_i}{n \times \Delta x}$$
$$\sum_{i=1}^{n} f_i \times \Delta x = 1 \qquad (3)$$

the histogram of the f_i constitutes image of the *pdfs* aleatory variable. The tests of hypothesis will confirm or less such affirmation. From the values of the experimental determination they have been valued some characteristics of the sample that constitute estimates of the corresponding characteristics of the aleatory variable. In fact, the assessment of mean and standard deviation of the single variable have been effected achieved to the following formulation:

$$\hat{\mu} = \frac{1}{n} \times \sum_{i=1}^{n} x_i = \bar{x}$$
$$\hat{\sigma}^2 = \frac{1}{n} \times \sum_{i=1}^{n} \left(x_i - \bar{x} \right)^2 \qquad (4)$$

In the formulation of standard deviation, showing up "n" to the denominator to the place of "n-1", could be considered not "correct". The dimension, sufficiently ample, of the sample it eliminates this problem. The models of aleatory variable that, for the different parameters in analysis, reproduce better the empirical distributions are Normal variable, Exponential variable;, Gamma variable. The Gamma function is, in general, the model of aleatory variable that better interpolates the empirical distribution of headways.
The hypotheses effected around the adaptability of the statistic models to the distributions of empirical frequency are been verified through the aid of the tests of hypothesis of "Kolmogorov-Smirnov" and $\chi 2$.
The values obtained in terms of relative frequencies have been correlated with the assumed values, in correspondence of the time gaps in minutes of the Gamma function with parameter equal to 1. Through the test of the $\chi 2$ the exact correspondence between the theoretical curve and that experimental has been determined. The graphic representation on the density of frequency and the various classes is showed in the following graphs.

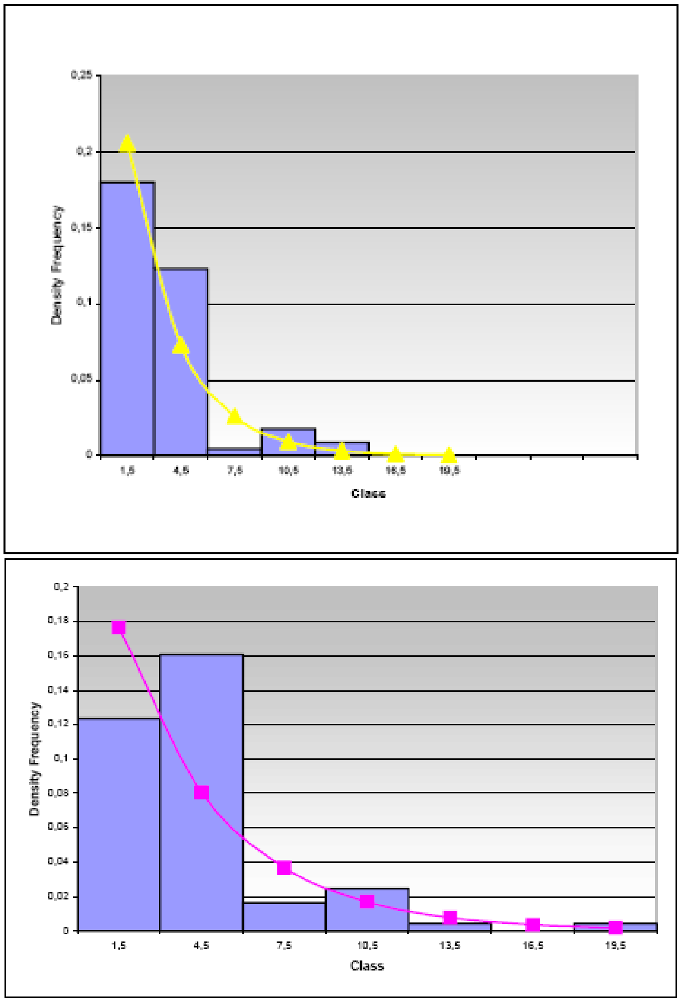
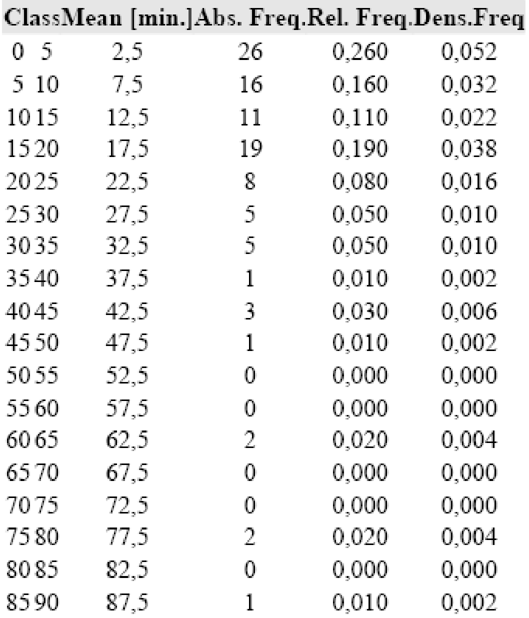


Fig. 8: Distance separation Distribution (Gamma with parameter equal to 1)in the case MM (Departure – Departure and Arrival - Arrival).

5 The aircraft sequencing model

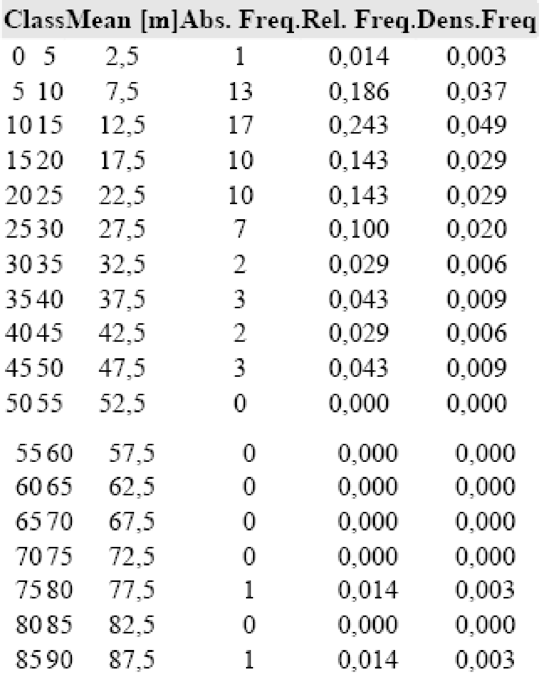
At the end of search an algorithm of calculation to optimize, to back, the flight operations of the airplanes in the International airport in Naples it is implemented. In this way, opportunely applying the model of calculation, it would be able sequencing airplanes on the airport both in the landing and in takeoff operations, determining the minimum relative time gap and, accordingly, the maximum number of airplanes that can operate in the airport in a determined period respecting the constrain of the acceptable delay individualized by the theoretical distributions.. Likewise to how much already express in the previous paragraph it is inferred by experimental data the theoretical distribution of delay relate to single operation and weight class. In other words we have analyzed and recorded, for every airplane, the difference between the scheduled time and the actual time. Such differences represents the above mentioned delay for flight operation. These sample represents database for the statistical inference method, through which, it is determined the theoretical function that approximate experimental shape.

Table 7: Experimental distribution of M class aircraft in the landing



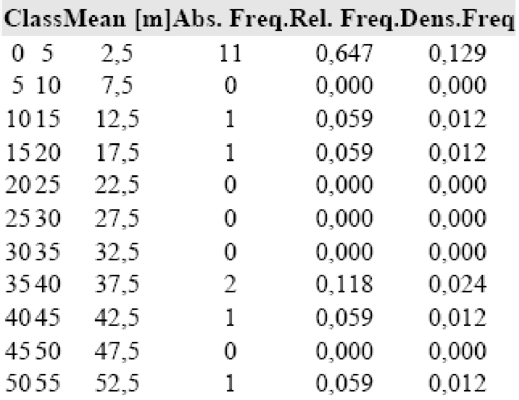
Class	Mean [min.]	Abs. Freq.	Rel. Freq.	Dens.Freq
0 5	2,5	26	0,260	0,052
5 10	7,5	16	0,160	0,032
10 15	12,5	11	0,110	0,022
15 20	17,5	19	0,190	0,038
20 25	22,5	8	0,080	0,016
25 30	27,5	5	0,050	0,010
30 35	32,5	5	0,050	0,010
35 40	37,5	1	0,010	0,002
40 45	42,5	3	0,030	0,006
45 50	47,5	1	0,010	0,002
50 55	52,5	0	0,000	0,000
55 60	57,5	0	0,000	0,000
60 65	62,5	2	0,020	0,004
65 70	67,5	0	0,000	0,000
70 75	72,5	0	0,000	0,000
75 80	77,5	2	0,020	0,004
80 85	82,5	0	0,000	0,000
85 90	87,5	1	0,010	0,002

Table 8: Experimental distribution of M class aircraft in the takeoff .



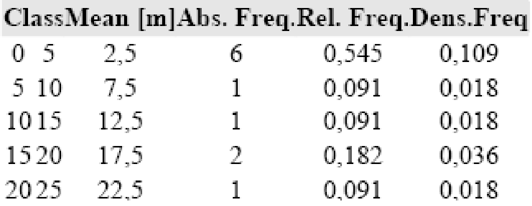
Class	Mean [m]	Abs. Freq.	Rel. Freq.	Dens.Freq
0 5	2,5	1	0,014	0,003
5 10	7,5	13	0,186	0,037
10 15	12,5	17	0,243	0,049
15 20	17,5	10	0,143	0,029
20 25	22,5	10	0,143	0,029
25 30	27,5	7	0,100	0,020
30 35	32,5	2	0,029	0,006
35 40	37,5	3	0,043	0,009
40 45	42,5	2	0,029	0,006
45 50	47,5	3	0,043	0,009
50 55	52,5	0	0,000	0,000
55 60	57,5	0	0,000	0,000
60 65	62,5	0	0,000	0,000
65 70	67,5	0	0,000	0,000
70 75	72,5	0	0,000	0,000
75 80	77,5	1	0,014	0,003
80 85	82,5	0	0,000	0,000
85 90	87,5	1	0,014	0,003

Table 9: Experimental distribution of L class aircraft in the landing



Class	Mean [m]	Abs. Freq.	Rel. Freq.	Dens.Freq
0 5	2,5	11	0,647	0,129
5 10	7,5	0	0,000	0,000
10 15	12,5	1	0,059	0,012
15 20	17,5	1	0,059	0,012
20 25	22,5	0	0,000	0,000
25 30	27,5	0	0,000	0,000
30 35	32,5	0	0,000	0,000
35 40	37,5	2	0,118	0,024
40 45	42,5	1	0,059	0,012
45 50	47,5	0	0,000	0,000
50 55	52,5	1	0,059	0,012

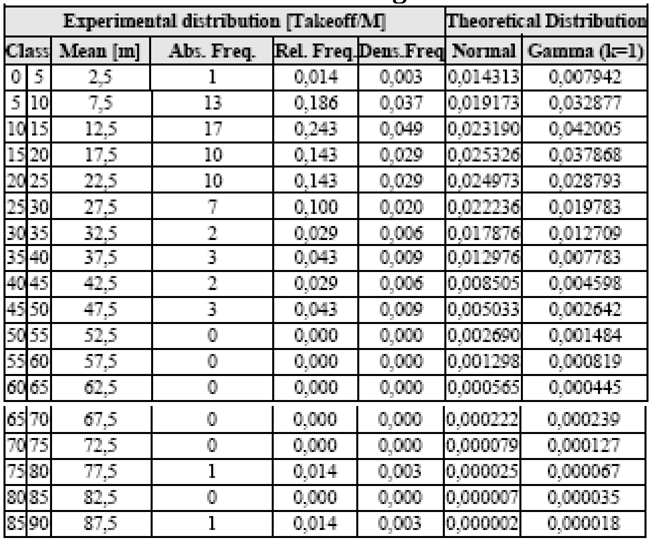
Table 10: Experimental distribution of L class aircraft in the takeoff



Class	Mean [m]	Abs. Freq.	Rel. Freq.	Dens.Freq
0 5	2,5	6	0,545	0,109
5 10	7,5	1	0,091	0,018
10 15	12,5	1	0,091	0,018
15 20	17,5	2	0,182	0,036
20 25	22,5	1	0,091	0,018

In synthesis one table and the consequent graph are brought related to the analysis of statistic inference considering two theoretical function: Normal and gamma distributions. The theoretical distributions of the delays are always Gamma functions with unitary parameter (K).

Table 11: Comparison among Experimental distribution and Theoretical distribution of delay of M class of weight



Experimental distribution [Takeoff/M]						Theoretical Distribution	
Class		Mean [m]	Abs. Freq.	Rel. Freq.	Dens.Freq	Normal	Gamma (k=1)
0	5	2,5	1	0,014	0,003	0,014313	0,007942
5	10	7,5	13	0,186	0,037	0,019173	0,032877
10	15	12,5	17	0,243	0,049	0,023190	0,042005
15	20	17,5	10	0,143	0,029	0,025326	0,037868
20	25	22,5	10	0,143	0,029	0,024973	0,028793
25	30	27,5	7	0,100	0,020	0,022236	0,019783
30	35	32,5	2	0,029	0,006	0,017876	0,012709
35	40	37,5	3	0,043	0,009	0,012976	0,007783
40	45	42,5	2	0,029	0,006	0,008505	0,004598
45	50	47,5	3	0,043	0,009	0,005033	0,002642
50	55	52,5	0	0,000	0,000	0,002690	0,001484
55	60	57,5	0	0,000	0,000	0,001298	0,000819
60	65	62,5	0	0,000	0,000	0,000565	0,000445
65	70	67,5	0	0,000	0,000	0,000222	0,000239
70	75	72,5	0	0,000	0,000	0,000079	0,000127
75	80	77,5	1	0,014	0,003	0,000025	0,000067
80	85	82,5	0	0,000	0,000	0,000007	0,000035
85	90	87,5	1	0,014	0,003	0,000002	0,000018

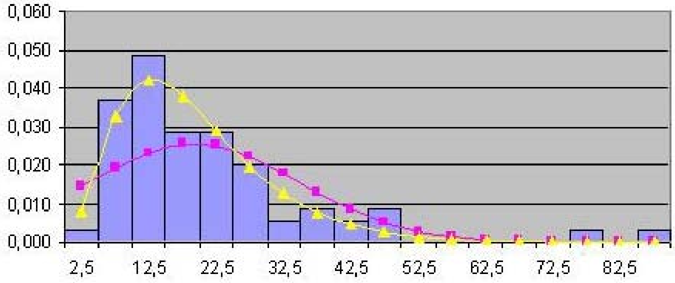


Figure 9: Comparison among Experimental distribution and Theoretical distribution of delay of M class of weight.

Beginning from deduced theoretical delay distributions have been determined the mean values for every operation and weight class:

Table 12: Mean delay

Operation and Type class	Mean Delay
Takeoff M	20'
Landing M	16'
Takeoff L	8'
Landing L	12'

Such above delay constitute the acceptable value for every weight class of aircraft and will be utilized in the optimization model.
The problem of sequencing aircraft near the terminal area satisfy some of the "system objectives":

- Airline and passengers (passengers delay, crew costs, aircraft utilization);
- Air traffic controllers (safety and workload);
- Pilots;
- Airport managers.

The model has been implemented in a critical period with length near to 1 hour.
The mathematical form is:

$$\min \sum_{i=2}^{n} (t_{is} - t_{ia})$$

with constraints:

$$t_{1s} = t_{1a}$$

$$\mathrm{t_{is}} = \mathrm{t_{i-1,s}} + \delta_{\mathrm{ij}} \quad \text{with } \mathrm{i} \neq \mathrm{j}$$

$$(\mathrm{t_{na}} - \mathrm{t_{1a}}) = (\mathrm{t_{ns}} - \mathrm{t_{1s}})$$

$$\text{if } \mathrm{t_{is}} = t_{ia} \quad \text{then} \quad \mathrm{t_{is}} = t_{ia}$$

$$\text{if } \mathrm{t_{is}} \le t_{ia} \quad \text{then} \quad \mathrm{t_{is}} \ge t_{ia} - 15'$$

$$\text{if } \mathrm{t_{is}} \ge t_{ia} \quad \text{then} \quad \mathrm{t_{is}} \le t_{ia} + 15'$$

where

t_{is} is the landing time of the *i* aircraft after sequencing;

t_{ia} is the landing time of the *i* aircraft before sequencing;

δ_{ij} is an element of distance separation matrix, above determined;
This model denoted with ASP term (Aircraft Sequencing Problem) represents a special case of *Traveling Salesman Problem*. We implemented and searched the results with MATLAB software.
An alternative mode to determine the optimal or local solution is the heuristic algorithm.
To find an improved sequence of the flights, local search can be used. Local search uses a neighborhood of the current solution to find a new (improved) solution. The neighborhood is defined in such a way that new sequences will be "close" to the current sequence, meaning they are very similar. This means the corresponding LP formulations will also be. LP solvers are able to solve such a formulation very efficiently by using the previous solution.
The general local search algorithm is given below.

```
LOCAL SEARCH()
1       S = initial feasible solution
2       while there is a neighbor of S of better quality
3       do S = neighbor of S of better quality
```

Next we will specify how to find an initial feasible solution, the definition of the neighborhood and the selection procedure for a neighbor of better quality. There are standard techniques available to do this. However, it is beneficial to use problem specific features in these procedures.
The critical period of September 2 2003 has been analyzed. Such period extended between 2 p.m. and 3.35 p.m. Redefining sequencing with the optimization model, that is defined above, valued through the express matrix in minutes shown in previous paragraph, the duration of the critical period is calculated that results lower and equal to 1h 17m 03s. In general with the application of this model we are successful to obtain, in static condition, a delay abatement equal to around 18%.

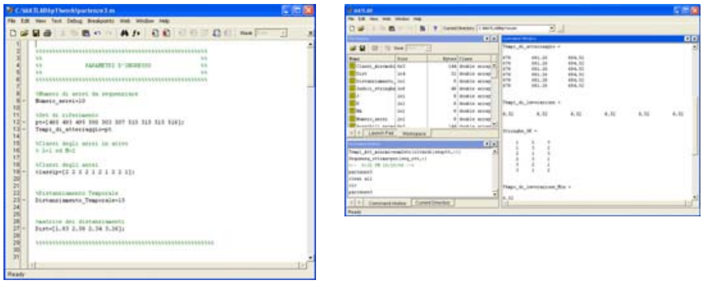


Figure 10: Matlab implementation.

Table 13: Results with algorithm application

CLASS	ACTUAL TIME(min)	TIME AFTER SEQUENCING (min)
M	857	857,00
L	870	859,34
M	870	861,92
M	875	865,18
M	880	868,44
M	881	871,7

6 Conclusion and research evolution

The static model is the least restrictive depiction of terminal area operations. We assume that there are N aircraft to be sequenced, and that we know in advance the operation time of each aircraft into the terminal area. In this way we are far to the real work of ATC controllers, but this is a necessary step in relation to determine real delay economy.

We are update the above model implementing this logic process in the dynamic machine that determine step by step and in real time a optimum operation sequences.

Furthermore we try to solve a problem with an high number of variables with a heuristic approach. The topic is still of extreme interest because of the increasing structural complexity of the models due to the constraints imposed by the "real systems" representation. A possible approach (the *TSP* heuristic) will be proposed to optimize the number of aircraft in the landing operation. A further evolution is to try to solve an algorithm with landing and take-off operation and with two or more runway in the same airport.

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