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Strategy for Attending Takeoffs and Landings to Reduce the Aircraft Operating Costs and the Passenger Delays

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The objective of this research was to establish and evaluate a strategy for attending to the takeoffs and landings at congested airports, in order to reduce aircraft operating costs and passenger delay times. The continuous growth of air transport activity has created congestion at many major airports worldwide. As a consequence, aircraft must often remain in waiting lines before they could be attended onto the runways for takeoff or landing. This in turn increases the aircraft operating costs and passenger discomfort. In the strategy proposed the traditional rule for attending to aircraft, on a first-come-first-served basis, was substituted with a sequence that reduces operating costs and passenger delays. The order of attention given to each aircraft was obtained using a heuristic algorithm that did not require enumeration of all the possible sequences. Consequently, the solution could be obtained in a short time. Results when using this strategy showed that significant reductions of up to 47.6% in operating costs and 73.2% in passenger delays could be achieved. The main contribution of this paper is the establishment of a strategy that makes possible these savings. The amount of benefits achieved depends on the proportion of aircraft wake turbulence classes that operate in a given airport. In general, the largest benefits are obtained when there is a mixture of different classes and when they are in a proportion of 40% small and 60% heavy. By utilizing the strategy proposed herein it is possible to obtain significant benefits for both airlines and passengers.

Keywords: Airport, congestion, heuristic algorithm, operating cost, passenger delay, strategy

1. Introduction

Congestion in transportation occurs when demand from the infrastructure exceeds capacity, causing travel delays as one of the main symptoms (Roosens, 2008). Since several years ago it has been reported that there is a lack of sufficient airport capacity to meet air traffic demands. This has resulted in congestion problems and delays in the aviation system at many major airports around the world (Hamzawi, 1992). There has been a rapid increase of air traffic over the past six

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decades worldwide, and this trend is forecasted to continue. The result has been severe congestion and very costly delays at more than 100 international airports around the globe. For instance, as traffic levels grew the first delays started to affect European airports in the late 70s and early 80s; with the traffic build-ups in the 1990s the delays increased (Eurocontrol, 2009). This congestion affects several of the airport sub-systems, most notably the runway which is the critical element in determining maximum capacity of any airport. As traffic continues to increase, so will these problems. For example, it is believed that the capacity problem in the United States (USA) and the Europe Union (EU) will probably become worse after the implementation of the open skies agreement (Turner, 2007). According to recent studies if nothing is done to avert the problem, 60% of European airports will be heavily congested by 2025 (ICAO and McGill University, 2006).

Today, hub congestion is a major concern because it causes significant problems at airports such as flight delays, cancellations and missed connections that consequently affect both airlines and air-travelers (Flores, 2010). This congestion increases airline operating costs because delays require these companies have to spend additional resources for the operation of aircraft, for example crew wages, jet fuel, and maintenance services when these vehicles must be held in line ups awaiting takeoffs or landings. In addition, the passengers are adversely affected wasting time as result of these queues.

Pilots must adhere to the regulations and procedures established by the air traffic control (ATC) which are standardized through international agreements. The primary purpose of ATC services worldwide is to prevent mid air and ground collisions, and to expedite and maintain an orderly flow of air traffic (ICAO, 1996). The assignment and authorization of arrivals and departures of aircraft is made by the ATC according to the sequence of request. Although there are certain exceptions, the rule followed is that of first-come-first-served (FCFS) (FAA, 2010).

Different solutions for mitigating the demand-capacity imbalance at airports have been proposed. In addition, various ATC decision-support tools have been developed in an attempt to match the demand to existing capacities that are more efficient and effective. However, all these tools have been applied, respecting the FCFS aircraft service priority rule. The partial exception is in the United States, where a traffic management advisor (TMA) has been used (Janic, 2009).

Furthermore, there has been other investigative work that abandons the FCFS-principle, but only considers landings. For instance, Soomer and Koole (2008) use the Aircraft Landing Problem (ALP) to illustrate various definitions of fairness that stem from the use of airline preferences. In this problem, a landing order and feasible landing times have to be determined for a set of flights at a given runway. Results show that it is possible to achieve more fairness while obtaining considerable cost savings as compared to the First Come First Served schedule. Another research project addresses the problem of scheduling aircraft landings at an airport (Wen, 2005). Given a set of airplanes and runways, the objective of this thesis was to minimize the total deviation from the target landing time for each plane. It was the first attempt to develop a branch-and-price exact algorithm for the ALP. Finally, Lee (2008) developed a dynamic programming algorithm for determining the minimum arrival cost schedule, using the aircraft-dependent delay costs. The proposed approach makes it possible to determine various tradeoffs considering multiple objectives in terminal-area operations.

The FCFS rule does not take into account that the operating costs and seating capacities of various aircraft are different. For instance, the operating cost of a Boeing 747, with 452 passenger capacity, is eightfold as compared to an ATR-42 with a 48 passenger capacity; and the Boeing 747 can transport 9.4 times more passengers than the ATR-42, see Table 1. Consequently, if the attention sequence of aircraft in a waiting line is reordered, it is possible to obtain significant savings in operating costs and reduce passenger delays. The solution to the problem consists of determining the sequence of attention that best reduces such costs and delays.

In this article a strategy is established and evaluated for takeoffs and landings at congested airports in order to reduce aircraft operating costs and passenger delays. The approach used for solving this problem consists of a procedure that obtains the aircraft attention order, without enumerating all the possible sequences. Consequently solutions can be obtained in a short time.

Results indicate that the benefits of applying the strategy proposed herein depend on the proportion of aircraft wake turbulence classes that operate at a given airport. This can significantly reduce operating costs, as much as 47.6% and passenger delays up to 73.2% when compared to the current FCFS rule.

Table 1. Typical operational characteristics of different aircraft

Aircraft	Operating cost per unit of time (€/s)	Typical seating	Wake turbulence class	Particular operation time (s)	
				Takeoff	Landing
Learjet 36	0.196	6	Small	78	79
EMB-120	0.299	30	Small	79	80
DHC 8-100	0.320	39	Small	71	96
ATR-42	0.331	48	Small	57	93
ATR-72	0.428	70	Large	48	78
Boeing 737-300	0.621	140	Large	66	67
Boeing 737-500	0.659	108	Large	65	66
DC-9-30	0.693	115	Large	65	66
MD-80	0.713	145	Large	59	80
Airbus A320	0.747	150	Large	62	84
Boeing 727-200	0.837	163	Large	41	61
Boeing 767-300	1.075	269	Heavy	52	53
Airbus A300-600	1.255	267	Heavy	52	53
Airbus A330-300	1.312	328	Heavy	53	54
Boeing 777-200	1.359	440	Heavy	47	64
DC-10-30	1.918	250	Heavy	50	67
Boeing 747-200	2.773	452	Heavy	54	67

Source: Original table, see text.

The operating costs illustrated in Table 1 were obtained by updating to 2010, the respective costs established by the International Civil Aviation Organization (ICAO) in 2000 (ICAO, 2000). According to the ICAO the total operating costs are the sum of the fuel costs and other costs. The component related with the jet fuel price was updated using the jet fuel price index established by the International Air Transport Association (http://www.iata.org). The index used (222.2) corresponds to that established for February 2010; this index was equal to 100 in the year 2000. In the case of other costs, an annual increase of 3% was considered; furthermore, an exchange rate of 1 Euro = 1.3572 dollars was factored in.

The number of seats in each aircraft might change depending on the class configurations applied by each airline. The values shown are typical figures.

The aircraft wake turbulence classes are based on their maximum certificated takeoff weight (MCTOW). Current US standards consider three aircraft classes (FAA, 2010): *Heavy* aircraft capable of taking off with weights of more than 255,000 pounds whether or not they are operating at this weight during a particular phase of flight; *Large* aircraft of more than 41,000 pounds, and up to 255,000 pounds; and *Small* aircraft carrying 41,000 pounds or less.

The particular operation time values are mean figures obtained from operations at Mexico City International Airport; these values could fluctuate in other airports. Note that in general the highest values belong to the small aircraft and the lowest to the heavy aircraft; therefore, the ICAO separation distance is implicit in the operation time.

2. Methodology

2.1 The approach enumerating all possible alternatives

The first approach to finding the optimum solution for a problem is to enumerate all the possible alternatives. This method is reliable, but since the amount of possible solutions rapidly increases with the amount of variables, it is not feasible to obtain a solution in a reasonable computing time, as is the case with problems considering a medium or large number of variables (Fernández, 2009).

In the case of a waiting line with n aircraft requesting service for landing or takeoff on the runway at a given airport, the number of possible sequences to attend to these would be n!

The formulation of the problem is as follows: consider that the runway of an airport must attend to the requests for service of a certain number of aircraft n = {A, B, C, ..., N}. Each one of the aircraft has two important characteristics: the operating cost per unit of time (c_i) and the particular operation time for service (t_i) during takeoffs or landings.

The total time for service that corresponds to the n-th aircraft according to the attention sequence is defined as τ_n. This represents the interval of time between when aircraft n requests service and when this is completed. Note that the total time for service for any aircraft, in the air or not, is equal to the sum of the particular operation times of the aircraft being attended to, plus its own particular operation time.

In this manner, for a group of aircraft awaiting service on a given runway, the aircraft n will have a total service time equal to:

$$\tau_n = \sum_{i=1}^{i=n} t_i \qquad (1)$$

For a group of n aircraft the operating cost (OC) is:

$$OC = c_A(\tau_A) + c_B(\tau_B) + c_C(\tau_C) + \ldots \quad c_N(\tau_n) \qquad (2)$$

Exact solution for two aircraft

In the case of two aircraft (A and B) that are in a waiting line, there are two possible sequences (2! = 2). One way to deal with this is to attend first to aircraft A and then aircraft B (A→B); the other possibility is to attend to aircraft B first and later to aircraft A (B→A).

The operating costs for these cases are:

$$OC_{A,B} = c_A(\tau_A) + c_B(\tau_B) = c_A(t_A) + c_B(t_A+t_B) = c_At_A + c_Bt_B + c_Bt_A \qquad (3)$$

$$OC_{B,A} = c_B(\tau_B) + c_A(\tau_A) = c_B(t_B) + c_A(t_B+t_A) = c_At_A + c_Bt_B + c_At_B \qquad (4)$$

Note that the sequence of attention directly influences operating costs. In the aforementioned situation the minimum operating cost will correspond to the minimum value of the product c_Bt_A or c_At_B. Also, note that the order of attention that minimizes operating cost depends exclusively on the c_i and t_i values. Therefore, the accuracy of these figures is critical for the results that are obtained.

Exact solution for three, four and five aircraft

In the case of three aircraft (n = 3), there are six possible sequences of attention (3! = 6).

Applying (2) the operating costs are:

$OC_{A,B,C} = c_A(t_A) + c_B(t_A+t_B) + c_C(t_A+t_B+t_C)$

$OC_{A,C,B} = c_A(t_A) + c_C(t_A+t_C) + c_B(t_A+t_C+t_B)$

$OC_{B,A,C} = c_B(t_B) + c_A(t_B+t_A) + c_C(t_B+t_A+t_C)$

$OC_{B,C,A} = c_B(t_B) + c_C(t_B+t_C) + c_A(t_B+t_C+t_A)$

$OC_{C,A,B} = c_C(t_C) + c_A(t_C+t_A) + c_B(t_C+t_A+t_B)$

$OC_{C,B,A} = c_C(t_C) + c_B(t_C+t_B) + c_A(t_C+t_B+t_A)$

In the case of four aircraft (n = 4), there are 24 possible sequences of attention (4! = 24). Using (2) it is possible to obtain the operating costs. Only the first and the last sequence are listed below.

$OC_{A,B,C,D} = c_A(t_A) + c_B(t_A+t_B) + c_C(t_A+t_B+t_C) + c_D(t_A+t_B+t_C+t_D)$

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$OC_{D.C,B,A} = c_D(t_D) + c_C(t_D+t_C) + c_B(t_D+t_C+t_B) + c_A(t_D+t_C+t_B+t_A)$

In the case of five aircraft (n = 5), there are 120 possible sequences of attention (5! = 120). Again applying (2) it is possible to obtain the operating costs. Here again, only the first and the last sequence are listed below.

$OC_{A,B,C,D,E} = c_A(t_A) + c_B(t_A+t_B) + c_C(t_A+t_B+t_C) + c_D(t_A+t_B+t_C+t_D) + c_E(t_A+t_B+t_C+t_D+t_E)$

. .

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$OC_{E,D,C,B,A} = c_E(t_E) + c_D(t_E+t_D) + c_C(t_E+t_D+t_C) + c_B(t_E+t_D+t_C+t_B) + c_A(t_E+t_D+t_C+t_B+t_A)$

Note that if there are a few aircraft in the waiting line, it is possible to solve the problem using a worksheet, but this rapidly becomes more difficult with more aircraft being considered. For instance, in the case of six aircraft, there are 720 alternatives; for 10 aircraft, there are 3,628,800 possible sequences; for 15 aircraft, there are more than one billion possible arrangements, 15! = 1,307,674,368,000; and for 20 aircraft there would be more than two trillions of possibilities, 20! = 2,432,902,008,176,640,000. Consequently, in these cases it is difficult to list all the alternatives on a worksheet.

2.2 The approach using a heuristic algorithm

The approach is based on three principles which were established from the observation of the behaviour regarding the sequences for queues of two, three, four and five aircraft. In all these cases the equations indicated in the sub-headings 2.1 and 2.2 were applied and the three principles were verified. Furthermore, the results show that by applying these principles that not only it is possible to reduce the operating costs and passenger delays, but also to obtain minimum values, at least for queues of two to five aircraft. Note that the concept of queue is referred as a virtual queue, because the aircraft could be flying and/or on the ground, awaiting authorization to land or takeoff.

Principle one: Consider a group of n-1 aircraft in which case the sequence of attention that produces the minimum operating cost is known. Assume that later the n-th aircraft is added; the order of attention that presents the minimum operating cost for this new group corresponds to some of the n alternatives in which the aircraft n is placed at the beginning, middle, or end of the attention sequence that offers the minimum operating costs initially considered for the n-1 aircraft.

For instance, consider that there are three aircraft A, B, and C; and that the sequence of attention that produces the minimum operating cost is A→B→C. Assume that later a fourth aircraft D is added. Then the order of attention that presents the minimum operating cost for this new group corresponds to some of the following four possible alternatives:

D→A→B→C

A→**D**→B→C

A→B→**D**→C

A→B→C→**D**

This principle creates the possibility to obtain the sequence that offers minimum operating cost faster and without enumerating and calculating all the possibilities. In the aforementioned case, it is necessary to calculate the values for only four cases, although there are a total of 24 alternatives. This means that 20 cases (83.33%) are discarded. This principle is even more advantageous when there are more aircraft in a waiting line. For example, if n = 5 aircraft, 95.83% alternatives (1-(n/n!)) are discarded; and for 9 aircraft, 99.99% cases are discarded. These figures show the advantage of applying this principle.

Principle two: The order of attention that produces the maximum operating cost is the inverse order of the sequence for the minimum operating cost.

For instance, if the minimum operating cost corresponds to the sequence A,B,C,… N, then the inverse order of that sequence (N,… C,B,A) produces the maximum operating cost.

Principle three: The value of the average operating cost is the mean of the minimum and maximum values.

For instance, using the equations obtained for two, three, four and five aircraft; and considering the following data taken from Table 1, it is possible obtain the respective operating costs.

C_A = 0.331 €/s; t_A = 57 s

C_B = 0.747 €/s; t_B = 84 s

C_C = 2.773 €/s; t_C = 54 s

C_D = 0.837 €/s; t_D = 61 s

C_E = 0.196 €/s; t_E = 78 s

The results are shown in Figure 1. It is observed that the operating cost values are scattered within a specific rank.

However, if the results are arranged according to their values, then it should be noted that there is an apparent symmetry among them, see Figure 2.

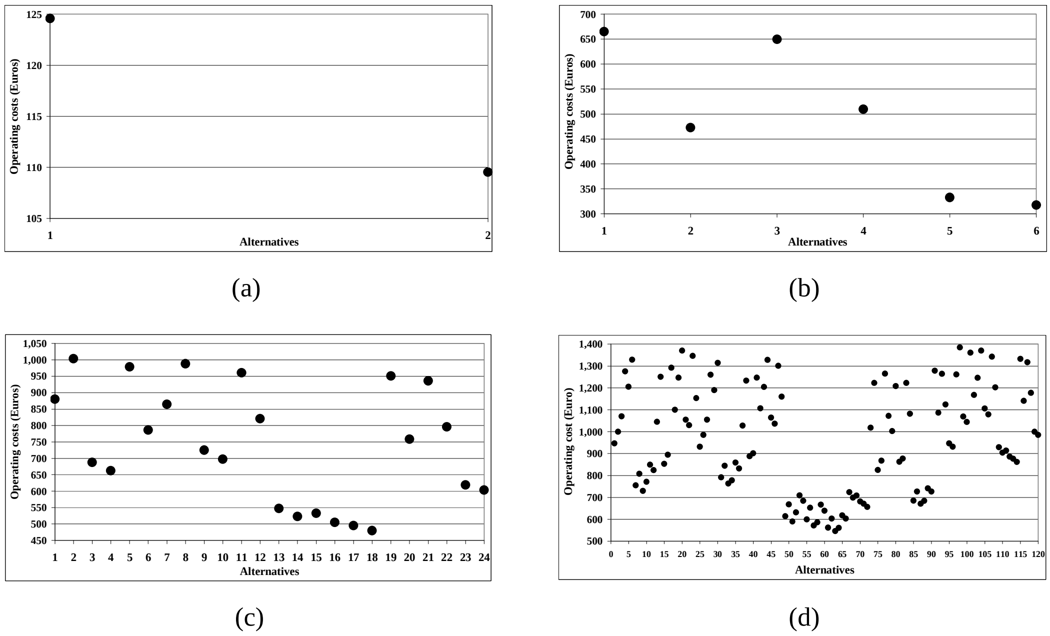

Figure 1. Operating costs for two (a), three (b), four (c) and five (d) aircraft

Source: Original figure.

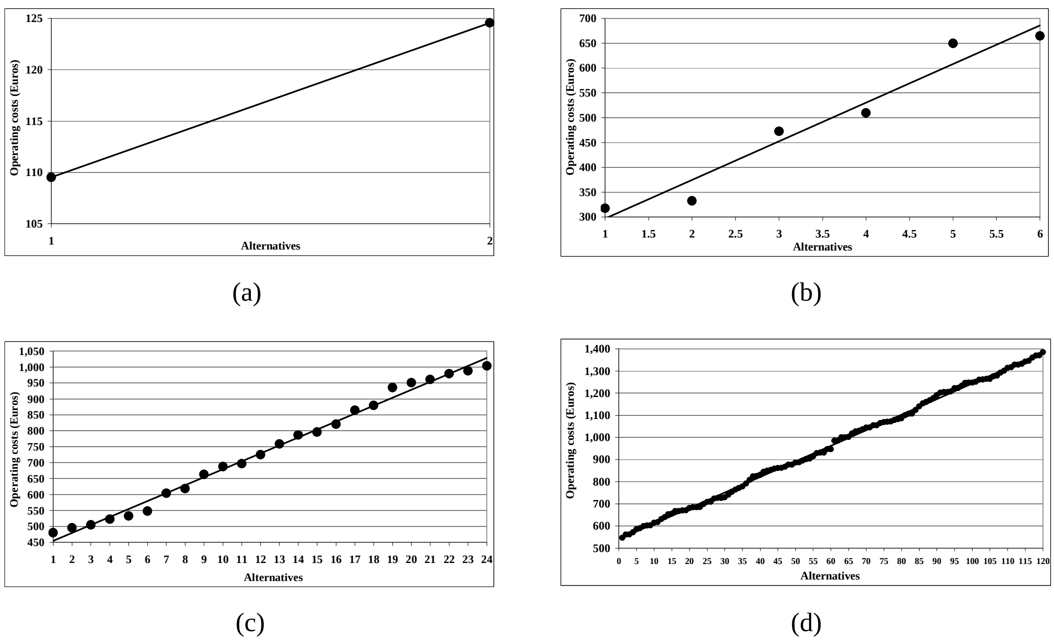

Figure 2. Operating costs arranged according to their values for two (a), three (b), four (c) and five (d) aircraft

Source: Original figure.

Note that a tendency line was incorporated into each graphic to better visualize the data distribution. In order to verify the symmetry, the differences between each pair of consecutive values were calculated for use in a table. Later, the first value was subtracted from the last, then from the second the penultimate, and so on; resulting in a table filled with zeros. This means that the operating cost values are symmetric in all cases.

Therefore, because there are symmetries in the values obtained in each sequence, it is sufficient to obtain the mean of the minimum and maximum values for calculating the average, without considering all the intermediate figures.

The approach applied to the passenger delays

By using the aforementioned procedure it is possible to obtain the order of attention that produces the minimum value for passenger delays (for instance, in terms of passenger-minute), if instead of the operating cost per unit of time (c_i) is used the number of passengers in each aircraft (p_i).

The passenger delay (PD) for a group of aircraft A, B, C, …,N, is:

$$PD_{A,B,C,\ldots N} = p_B(t_A) + p_C(t_A+t_B) + \ldots p_N(t_A+t_B+t_C+\ldots t_{N-1}) \qquad (5)$$

Note that this equation has the same structure obtained for the operating costs, see equations for three, four and five aircraft in sub-heading 2.1. Therefore, the equivalent principles previously pointed out apply to passenger delays.

3. Application of the methodology

The aforementioned methodology was applied to determine the potential benefits of reordering the sequences of attention given to aircraft, during takeoffs and landings, in a hypothetical airport. The benefits were quantified in terms of the reduction of operating costs and passenger delays.

It was assumed that approximately 50% of the movements on the runway were takeoffs and 50% landings, because this is the proportion that normally occurs in airports. In order to exemplify the application of the methodology two cases of queues were considered, five and ten aircraft. The average values of operating costs and passenger delays correspond to the current FCFS policy, because there is a trend toward these values when a group of operations are performed in a random manner. The values were obtained with the heuristic algorithm which corresponds to the proposed strategy. The data used to apply the methodology was taken from Table 1.

3.1 Case for queues of five aircraft

Table 2 shows the results for operating costs. In this case groups of five aircraft of different proportions according to wake turbulence classes, small, large and heavy, were considered. Because each group consisted of five aircraft, the minimum unit of increase was 20%. Note all the possible combinations of the three aircraft classes were considered.

This table is ordered according to the sixth column which is the difference between the fifth and fourth columns and represents reduction of operating costs utilizing the proposed strategy instead of the current FCFS rule. The last column shows reductions in percentage. It is noteworthy that the total time of service ranges from 4 minutes 37 seconds to 6 minutes 36 seconds.

In regard to the sequence of attention that reduces the operating costs and delays, results indicate that in all the cases these groups of aircraft were ordered according to their classes, and that the sequence for attending to these groups always followed this priority: heavy, large and small.

Also, it was noted that in most cases within the same aircraft class, the highest values of c_i for the operating costs, and p_i for the delays, corresponded to the aircraft that were attended to first.

Following the same procedure and structure used for the operating costs, Table 3 shows the results for delays, in terms of passenger-minute.

Table 2. Operating costs obtained for a queue of five aircraft considering the current FCFS rule and the strategy proposed herein

Percentage of aircraft at the queue, according to the wake turbulence class (%)			Operating cost (€)		Reduction of the operating costs considering the proposed strategy instead of the current FCFS rule	
			Proposed strategy	Current FCFS rule		
Small	Large	Heavy			€	%
100	0	0	315.14	340.29	25.15	7.39
0	100	0	598.70	646.31	47.61	7.37
80	20	0	322.49	393.73	71.25	18.10
20	80	0	513.42	596.76	83.33	13.96
60	40	0	360.00	452.68	92.68	20.47
40	60	0	430.33	532.84	102.51	19.24
0	0	100	1,256.47	1,436.66	180.19	12.54
0	80	20	669.53	885.27	215.73	24.37
20	60	20	563.39	835.04	271.65	32.53
40	40	20	473.80	767.57	293.77	38.27
80	0	20	389.37	687.50	298.14	43.37
0	20	80	1,082.20	1,382.39	300.19	21.72
60	20	20	431.22	735.40	304.18	41.36
0	60	40	791.83	1,103.24	311.41	28.23
20	40	40	678.67	1,047.04	368.36	35.18
20	0	80	1,007.56	1,381.86	374.31	27.09
0	40	60	925.69	1,303.03	377.34	28.96
40	20	40	623.98	1,026.80	402.82	39.23
60	0	40	576.75	1,007.00	430.24	42.73
20	20	60	854.91	1,296.03	441.12	34.04
40	0	60	795.52	1,286.28	490.76	38.15

Source: Original table.

3.2 Case for queues of ten aircraft

The same procedure used for queues of five aircraft was applied to queues of ten aircraft. In this case groups of ten aircraft were considered in all the possible combinations in relation to the three aircraft classes. Because each group consisted of ten aircraft, the minimum unit of increase was 10%. The results show that the total time of service ranges from 9 minutes 14 seconds to 13 minutes 12 seconds. In relation to the sequence of attention that reduces the operating costs and delays, it was noted the same behaviour occurred as in the case of five aircraft.

3.3 Analysis of results

In general when a queue has only one class of aircraft the benefits are lower than when there is a mixture of classes. These benefits are established as the reductions of operating costs and passenger delays, considering absolute or percentage values. In relative terms, the results showed that significant reductions of up to 47.6% in operating costs and 73.2% in passenger delays could be achieved, depending on the proportions of aircraft classes.

In the case of five aircraft the maximum benefits in absolute values for operating costs and delays were obtained using a proportion of 40% small and 60% heavy; however, for the case involving ten aircraft, the maximum benefit in terms of operating costs corresponded to a proportion consisting of 60% small and 40% heavy, and regarding delays there were 40% for small and 60% for heavy.

Table 3. Delays obtained for a queue of five aircraft considering the current FCFS rule and the strategy proposed herein

Percentage of aircraft at the queue, according to the wake turbulence class (%)			Delay (passenger-minute)		Reduction of delays considering the proposed strategy instead of the current FCFS rule	
Small	Large	Heavy	Proposed strategy	Current FCFS rule	Passenger-minute	%
100	0	0	281.13	406.76	125.63	30.88
0	100	0	1,222.23	1,457.32	235.09	16.13
80	20	0	343.36	674.16	330.80	49.07
20	80	0	858.43	1,253.47	395.04	31.52
0	0	100	2,740.91	3,184.93	444.01	13.94
40	60	0	584.02	1,039.08	455.06	43.79
60	40	0	409.45	880.40	470.95	53.49
0	80	20	1,200.69	1,811.22	610.54	33.71
0	20	80	1,978.28	2,696.92	718.64	26.65
0	60	40	1,249.13	2,079.91	830.78	39.94
20	60	20	806.17	1,644.83	838.67	50.99
80	0	20	321.58	1,201.83	880.25	73.24
0	40	60	1,631.33	2,559.28	927.95	36.26
40	40	20	596.18	1,555.49	959.30	61.67
60	20	20	395.67	1,377.06	981.38	71.27
20	0	80	1,616.93	2,664.58	1,047.65	39.32
20	40	40	956.99	2,030.99	1,074.00	52.88
40	20	40	702.62	1,922.67	1,220.05	63.46
20	20	60	1,274.34	2,502.72	1,228.38	49.08
60	0	40	498.17	1,774.46	1,276.29	71.93
40	0	60	1,012.15	2,431.35	1,419.19	58.37

Source: Original table.

The maximum benefit is obtained when there is a mixture of small and heavy classes (zero percentage of large class), because the heavy aircraft with the highest C_i and lowest t_i values are attended to first, and the small aircraft with the lowest C_i and highest t_i values are attended later.

The influence of the aircraft size in determining the priority of attention is related to the operation costs per unit of time and the particular operation times of each class. Due to the steepest growing of c_i from the small class to the heavy class, as compared with the growth of the corresponding t_i, the contribution to total costs of heavy class aircraft grows faster regarding time than those of smaller classes. Therefore, it seems reasonable to attend to the bigger aircraft first and then the smaller ones.

Also, it was generally observed that a proportion of 80% small class and 20% heavy class were accommodated when the maximum benefit in relative terms was obtained. Consequently, this proportion of aircraft appears to follow the Pareto principle, an issue to consider for future research.

The length of the queue is proportional to the potential benefit For instance, in the case of five aircraft queues a reduction of up to €490.76 in the operating costs was achieved, but for ten aircraft queues the reduction was up to €1,523.14; which implies that duplicating the size of the queue, triples the benefits. In the case of the delays, for queues of five aircraft a reduction of up to 1,419.19 passenger-minute was achieved, but for ten aircraft queues this reduction was up to 5,313.02 passenger-minute; therefore, by duplicating the size of the queue, the benefits are increased almost fourfold.

The relevance of aircraft size to determine the priority of attention offered in the queues was tested measuring the Spearman correlation coefficient R of aircraft size (in terms of MCTOW) versus attention priority. In many cases high values of R were obtained with good p-values for significance, in general for combinations of several size classes. However, for groups with a single class of aircraft, non-significant low values of R resulted. Also, it was noted that in order to obtain the minimum operating cost, the heavy class always had priority over the large and small classes, and the large class had priority over the small class. Therefore, it seems that size of aircraft represented by its class is an important issue in order to determine the priority of attention. However, the order of attention within the same aircraft class is not always defined by the MCTOW. Although the aircraft size is an important factor to obtain the order of attention that minimizes the operating cost, it is not a determining factor.

4. Discussion

It is important to point out that the proposed strategy does not reduce the size of the queues. It simply reorders the sequence of attention given to each aircraft to reduce the operating costs and passenger delays.

Although the greatest benefits of the proposed strategy were obtained when there was a mixture of different aircraft classes, and when they were in a proportion of 40% small and 60% heavy, this does not mean that it is recommended to manage that mixture. On the contrary, the recommendation is to manage a homogenous class of aircraft during takeoffs and landings. The interpretation of the findings is that in airports that manage a mixture of aircraft classes, it is possible to reduce negative effects for operators and passengers by changing the sequence of attention given to the aircraft.

According to the results, it is evident that in order to reduce the operating costs and delays, the largest aircraft must be attended to first and the smaller ones later. There are two important implications here. On the one hand, this condition promotes the use of larger aircraft because they will have the advantage of being attended to first. On the other hand, the use of large aircraft can decrease runway congestion, although it could congest other processing facilities within the airport. Certain studies indicate that the area that would be most affected is the baggage claim system (Chiu and Walton, 2002 and 2003). Therefore, the application of the suggested strategy must also take this into consideration.

Note that the total time of service represents the maximum value that an aircraft should wait before being attended to; consequently, this value could be the reference used to determine if the proposed strategy should be applied or not. For instance, if aircraft must not be delayed more than 15 minutes, it is possible to apply this strategy for queues of ten aircraft.

During 2009, in Europe alone, 38% of flights were delayed for departure and 36% for arrival. Also, it was reported that among the top 50 airports most affected in regarding departures, that the average delay per movement ranged from 9.3 to 18.9 minutes; and for the top 50 airports most affected regarding arrivals, this ranged from 8.9 to 19.3 minutes (Eurocontrol, 2010). In addition statistics for the top 30 airports worldwide according to aircraft movements during 2008 show that 23 of these airports are located in America, 21 are in USA and the others are in Toronto and Mexico City; six are in Europe, Paris/Charles-De-Gaulle, Frankfurt, London/Heathrow, Madrid/Barajas, Amsterdam and Munich; and the last is in Asia, Beijing (Airports Council International, 2010). Airports with great activity have greater congestion that represents longer queues and delays; for instance, the six aforementioned European airports reported significant delays (Eurocontrol, 2010). Consequently, there is substantial potential for applying the proposed strategy at many airports in America, Europe and Asia.

There are several administrative policies that could promote the application of the strategy for attending to takeoffs and landings in order to reduce the aircraft operating costs. In general terms there are three alternatives:

Option 1. In this case each airline receives the increases or reductions in its operating costs. In this option some airlines will be granted reductions in operating costs while others will incur increases. However, the group of aircraft as a unit reduces its total operating cost.

Option 2. In this alternative part of the benefits obtained by the airlines that reduced operating costs are transferred to the airlines that received increases. The magnitude of such transfers has a maximum value that could maintain the original operating cost of the airlines initially affected. In this case the benefits initially gained by the airlines attended to first are reduced, but the aircraft that originally had increased operating costs now reduce these costs or at the very least maintain original values.

Option 3. A third possibility occurs when a greater proportion of the benefits are received by the airlines that initially had increased operating costs. The magnitude of the transfers is substantial enough so that these airlines reduce their original operating costs. Using this option all the airlines benefit because they all can reduce their overall operating costs.

In order to illustrate the application of the three options, assume that there is a queue of two aircraft, the first is an ATR-42 and the second a Boeing 747, and both wish to land at an airport. Using the information found in Table 1 the total operating cost is:

$OC_{ATR\text{-}42,Boeing747} = 0.331(93) + 2.773(93+67) = 30.78 + 443.68 = €474.46$

But if the strategy proposed herein is implemented to reduce the operating costs. The Boeing 747 will be attended to first and then the ATR-42; therefore, the total operating costs is:

$OC_{Boeing747,ATR\text{-}42} = 2.773(67) + 0.331(67+93) = 185.79 + 52.96 = €238.75$

According to option one, the Boeing 747 reduces operating costs (€443.68→€185.79), and the ATR-42 increases costs (€30.78→€52.96), although taken together the reduction of total operating cost is €238.75 instead €474.46. Applying option two, part of the benefits obtained by the Boeing 747 is transferred to the ATR-42, in order to maintain original operating cost. In this case, the Boeing 747 should transfer €22.18 (€52.96 - €30.78) to the ATR-42; therefore, the Boeing 747 has an operating cost of €207.97 (€185.79 + €22.18). Finally, if option three is applied, the Boeing 747 transfers €52.96 to the ATR-42 which means that the operating cost for this aircraft is zero. However, the operating cost of the Boeing 747 is €238.75. Using this option both aircraft benefit because all reduce operating costs. The Boeing 747 reduced its operating costs from €443.68 to €238.75 and the ATR-42 reduced its operating cost from €30.78 to zero.

Option one is the most attractive for the airlines that are attended to first, but it is less attractive for the airlines attended to at the end of the queue. Using the second alterative it is possible that some aircraft will reduce their operating costs, namely those attended to first; and those attended to later will at the very least not increase their operating costs. Finally, the third option is probably the most viable because all the aircraft in general reduce their operating costs.

In addition to promoting the strategy, it is necessary to take at least two measures into consideration in order to implement it. These include: a) Measures related to the slot system; and b) Measures regarding new procedures for instrument approach and departure of aircraft. The first measure requires negotiations and agreements among the airlines that operate in a given airport, in order to modify the current slot system. This measure possesses economic implications that are closely related to the administrative policy that will promote the application of the strategy. The second measure is a technical issue that requires a solution for practical implementation of the strategy. It implicates the development of more flexible procedures than the methods currently utilized, because the new strategy does not apply the traditional FCFS rule.

5. Conclusion

The approach used for solving the problem is a procedure that obtains the aircraft attention order that reduces operating costs and passenger delays, without enumerating all the possible sequences. The advantage of this approach is that it does not require a lot of time to obtain the solution.

The results demonstrated that significant reductions of up to 47.6% for operating costs and 73.2% for passenger delays could be achieved by using the proposed strategy. These benefits depend on the proportion of the aircraft wake turbulence classes that operate in a given airport. In general, the largest benefits are obtained when there is a mixture of different classes and when they are in a proportion of 40% small and 60% heavy. As a result, if the proposed strategy was applied it is possible to obtain significant benefits for both airlines and passengers.

It was noted that in order to reduce the operating costs and delays, the largest aircraft must be attended to first and the smaller ones later. This condition promotes the use of large aircraft, but it could also congest other processing facilities within the airport, for instance, the baggage claim system.

There is a definite potential for applying the proposed strategy at many airports in America, Europe and Asia.

Three administrative policies were considered for promoting the proposed strategy. Apparently, the third option, in which all the aircraft reduce their operating costs, is the most viable. But, the feasibility of each option depends on the types and quantities of aircraft present in the waiting lines in each specific airport.

Although the potential benefits of applying the proposed strategy were quantified, future investigative work would be to link it up with a simulation model in order to calculate the benefits not only in a specific size of queue, but in a typical daily operation to obtain figures that would support the implementation of the strategy. Such a model will permit the establishment the actual length of queues and their composition considering the different classes of aircraft.

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