International Transport Forum

Alternative Solutions to Airport Saturation: Simulation models applied to congested airports

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Abstract

This paper explores several methods for coping with excess demand at airports through applying simulation modeling that focusses on how to use the existing airport infrastructure more efficiently. The introduction presents an overview of the importance of solving the airport saturation problem and sets out several approaches to solutions, which are divided into four distinct groups, or options. The fourth option applies operational practices and/or new technology to improve the airport procedures, including computer modeling and simulation. The document presents the application of simulation models to the capacity issues at the Mexico City Airport to demonstrate how to potentially alleviate congestion. Examples include redistribution of takeoffs and landings to increase runway capacity; reduction of air traffic movements through allowing operations of aircraft with greater capacity; deployment of new technologies to increase runway capacity; and by means of new operational procedures, changing the aircraft waiting sequence to reduce delays.

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Introduction

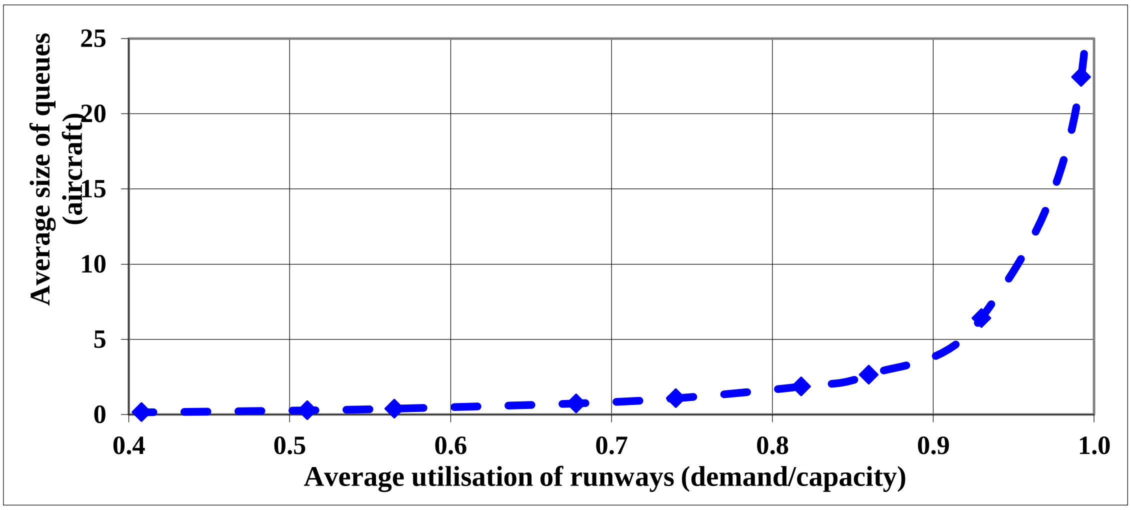
The objective of this paper is to explore several different ways of coping with the imbalance between the available airport capacity and the traffic demand through application of simulation modelling as a tool to explore potential solutions to the capacity problem, focusing on the efficient use of existing airport infrastructure.

According to the International Air Transport Association (IATA) the greatest problem of the aviation industry in Latin America is the lack of an adequate infrastructure, this happens mainly in countries like Brazil, Mexico, Argentina and Colombia, where there are congested airports that operate to their limit of capacity or require improvements (http://aerolatinnews.com/2014/12/12/infraestructura-el-problema-para-aviacion-en-al/). An analysis performed by EUROCONTROL (2013) concluded that in 2012 "there were just 6 airports that were congested in the sense of operating at 80% or more of their capacity for more than 3 hours per day. In the most-likely scenario of the 2035 forecast, this climbed to more than 30 airports in 2035". In the European Union "one of the worst transport problems is congestion, especially on the roads and in the skies. Congestion costs Europe about 1% of its GDP every year and also causes heavy amounts of carbon and other unwelcome emissions" (EU, 2014), and according to the Aviation Council International (ACI, 2017) the consumers in Europe are paying EUR 2.1 billion a year in additional air fares, due to capacity constraints at airports. In the United States, according to the FAA, air traffic at airports of all sizes will continue to increase in the foreseeable future, reaching 1 billion by 2029 and exceeding 1.1 billion by 2034. According to the FAA's FACT 3 report on airport capacity needs in the United States, the three major New York area airports (John F. Kennedy, La Guardia and Newark Liberty) and Philadelphia International Airport will continue to experience major system constraints even after all currently planned capacity improvements are implemented. Aviation passengers in the United States bear nearly USD 17 billion in additional costs every year due to flight delays (Mica, 2015), so the solution to this problem is undoubtedly of great practical importance.

The lack of sufficient airport capacity to meet the demand caused by the movement of passengers and aircraft, as well as the consequent problem that is generated in the saturation of airports and the delay of the operations, have become a common challenge at major airports in the world, impacting the mobility of people and cargo. Studies of air transport systems shows that delays and queues on runways begin to grow substantially when the demand exceeds about 80% of the available capacity of the system. The solution to the problem of airport congestion should therefore focus on finding ways to reduce the demand/capacity ratio. This can be achieved by increasing the capacity, reducing the demand, or combining both options (Hamzawi, 1992). Figure 1 shows how increasing the demand/capacity ratio changes the average size of the queues made up of aircraft waiting to use the runways at the Mexico City International Airport (AICM). These estimates were obtained through simulation modeling (Herrera, 2012).

The solution to the problem of airport congestion has been divided into four options (Figure 2). Option A is related to the incorporation of new infrastructure; this option increases the capacity of the entire airport or the capacity of some of its subsystems. Option B establishes mechanisms that reduce the demand for airport services. Option C, although it does not diminish the demand, redistributes operations, which results in greater operational efficiency of the airport. Finally, Option D, through operational or technological innovations also increases the efficiency of the airport (Hamzawi, 1992).

Figure 1. **Average sizes of queues on Mexico City International Airport runways as a function of the average utilisation of them**



Option A: Investment in new infrastructure

The development of new airports or the expansion of existing facilities directly increases the capacity of the system. However, such developments are often difficult due to funding constraints, environmental concerns and opposition by local communities to the development of new airports. Also, such developments cannot address the need for new capacity in the short term. For example, the construction of a new terminal usually requires between five and ten years to be completed.

Increasing the capacity of an existing facility may, however, not involve its physical enlargement as reconfiguration of the existing space may be sufficient.

Option B: Demand management

The reduction of demand at an airport can be achieved by shifting a portion of demand to alternate locations or other modes of transportation, for instance:

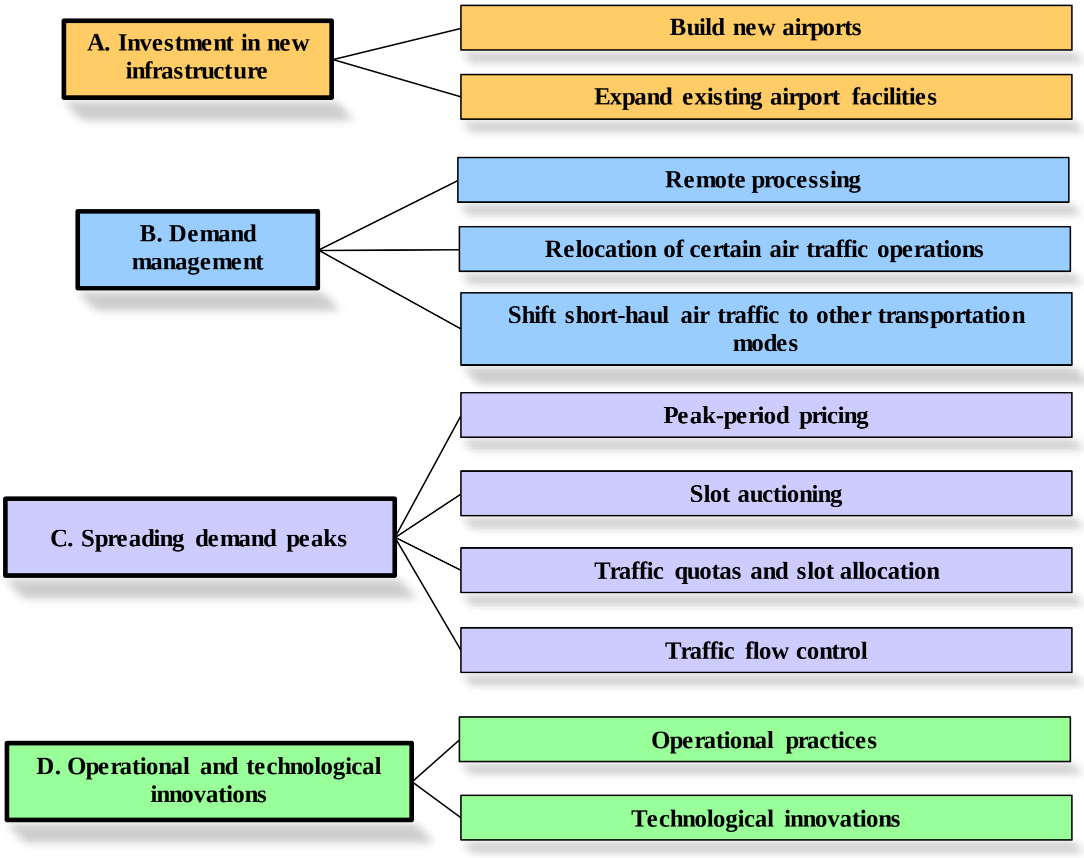
Remote processing: This proposal helps to reduce the demand in the airport facilities by servicing part of it at alternate or complementary locations outside the airport. In terms of the airport landside, this would apply mainly to the parking of vehicles, passenger processing and the allocation of aircraft gates.

Parking of vehicles outside the airport: When the capacity of the airport car parking facilities is insufficient to meet demand and cannot be expanded efficiently within the limits of the airport, additional parking facilities could be constructed outside the airport and connected to the terminal through a circulation system, for instance, using shuttle buses.

Processing of passengers outside the airport:This involves primarily the delivery of boarding passes and activities related to verification of baggage at a remote location, or at key locations within the city, where the sources and destinations of passengers are concentrated. It also includes the transport of passengers to the airport to complete the remaining activities related to the flight.

Remote positions for aircraft: Lack of sufficient positions for passenger embarking/disembarking may be compensated by the use of specialised vehicles to transport the passengers between the terminal building and their aircraft in a remote position.

Figure 2. **Options for balancing airport capacity and demand**



Source: Based on Hamzawi (1992).

Relocation of certain air traffic operations

Commercial operations: This proposal is based on a policy decision by the authority to relocate some segments of the commercial traffic operation (for instance international flights or charter operations), or certain airlines to other less-utilised or less-congested neighboring airports. This policy could be established by giving incentives to the airlines or may be forced through actions to relocate their operations.

General aviation: One method to maximise the use of available capacity at a busy airport is to restrict its use to non-commercial flights, such as general aviation operations.

Shift short-haul air traffic to other transportation modes

Replacement of short-haul (up to 500 km distances) flights with other transportation modes may release some degree of congestion at airports with high proportions of such traffic. An alternate mode could be high-speed surface transport link, for instance, a train.

Option C: Spreading demand peaks

This concept involves the adoption of certain economic and/or administrative measures aimed at modifying the demand profile to make it fit within the limits of available capacity. Therefore, this approach may be suitable for situations where further increase of airport capacity is not feasible or very expensive.

Although the expansion of an airport at the end may be inevitable, peak-spreading solutions can be implemented in far less time than it takes to build a new facility, with the advantage of delaying the need for expansion and reducing the great capital investment associated. There are two proposals to achieve this approach, one market-based and the other administrative.

Market-based measures

Peak-period pricing: This market-based approach uses prices as an instrument to regulate traffic demand. Commonly, it takes the form of surcharges (extra fees) on the use of the airport slots during busy hours of the day to encourage airlines to shift their flights out of the most congested periods to other less busy times or even to different airport sites.

Slot auctioning: In this case, the right to use the airport (landing or take-off) at a certain time during the day (slot) is sold to the highest bidder. In this way, the free market forces determine the cost, which is what users are willing to pay based on their perception of the value of the airport access at any given time.

Administrative measures

This approach is aimed at limiting the volume or type of air traffic that will be accommodated at an airport within the limits of some given capacity or acceptable level of delay.

Traffic quotas and slot allocation: Under this proposal maximum quotas are imposed on the number of aircraft landings and takeoffs and/or passenger volumes permissible within the limits of some specified capacity of the runway system, the aircraft gates and/or the air terminal building.

Traffic flow control: Flow control is a procedure of administration of air traffic assisted by computer, which does not explicitly restrict the access to the airport. This technique focuses on the dynamic control of traffic volumes to and from an airport in response to overall regional or national demand. This is accomplished through settings with computerised continual adjustments of the times of arrivals and departures from airports throughout the system. Usually the delay occurs in less costly ways, for instance, on the ground at the departure airport or en route rather than in a holding pattern at the destination airport.

Option D: Application of operational and technological innovations.

Apart from the methods of reducing congestion and the resulting delays mentioned above, another promising area of increasing airport capacity is through development and implementation of new technologies and innovations to maximise utilisation efficiency of the existing facilities.

Operational practice

Some innovative operational practices could be considered to improve the utilisation of airport capacity, for instance:

- Checking in at gate holding areas for high-density/shuttle operations where passengers have only carry-on luggage. This allows travelers to bypass the otherwise busy public concourse check-in counters.

- Adoption of common-use gate assignment operational strategies to maximise the utilisation of gate capacity as opposed to exclusive use of gates by airlines.

- Use of aircraft power push-backs that eliminates the need for the aircraft on gate to wait for a tug and endure the time-consuming operation of coupling and decoupling with the aircraft nose gear.

- To apply the knowledge of wake vortex behavior to increase capacity for airports with close-spaced parallel runways. Based on this information new criteria could be applied to reduce the current operational limits (Burnham et al., 2001).

Aircraft technology

This option focuses on two types of aircraft which would contribute to the relief of airport congestion on both the air and land side. The first type of aircraft, that uses tilt-rotor technology, combines the vertical landing and takeoff capabilities of helicopters with the speed, range and fuel economy of fixed-wing aircraft. Due to these features this type of aircraft (convertiplane) would not require the use of an airport for its operation.

Another option is to encourage utilisation of larger aircraft types (e.g. Airbus A380). Although this requires more complex operations, using biggest aircraft implies using fewer air traffic movements (ATMs) to transport the same number of travelers, or it could transport more users with the same number of operations.

Computer modeling and simulation

As part of the application of technological innovations, development and use of computer models to assess prevailing levels of service and to evaluate possible options for reducing congestion have been widely recognised. This tool could improve the efficiency of airport operations and capacity management. Such models could be used to simulate the movement of aircraft on runways, taxiways and platforms; the assignment of gates to aircraft; the flows of pedestrians in the terminal building; and the movement of vehicles through the ground transportation system.

Simulation models

The technique of simulation is one of the most widely used in operations research and management science to evaluate systems.

Simulation models commonly take the form of a set of assumptions about the operation of a system. These are expressed in the form of mathematical and logical relationships among its components. They can be used to investigate a wide variety of issues about the real world. These models are used as a tool of analysis, to predict the effects of changes in existing systems, or as a design tool to predict the behavior of new systems. Studies that use simulation models offer the following advantages:

- New policies, decision rules, organisational and operational procedures could be explored without altering the course of the system.
- A simulation model is quite realistic in the sense that it reproduces the characteristics of the modeled system with a high degree of accuracy.
- It is possible to apply the simulation in order to investigate the behavior for non-existing, often innovative systems.
- The equivalent operation of days, weeks or months of the real system could be simulated on a computer in just seconds, minutes or hours. On the other hand, if required, the representation of the actual time can be lengthened to observe in more detail the phenomenon under investigation.

- Responses “what if...?” to questions are obtained. This is particularly useful for the design of new systems or exploring different future scenarios.

Application of simulation models to congested airports, the case of Mexico City International Airport

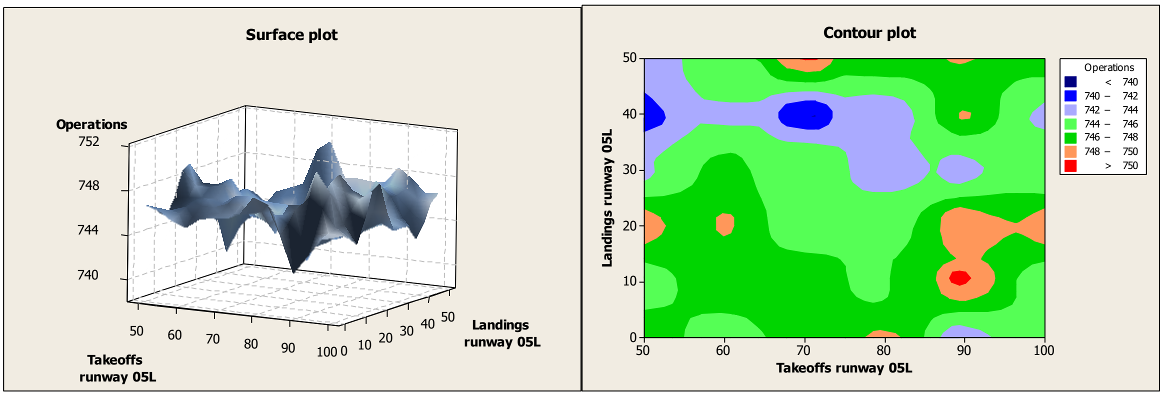
Mexico City International Airport (AICM) stands out as one of the most important airports in the world, since it appears regularly in the world’s top 50. In 2015 the AICM was the 45th biggest airport in the world in terms of the number of handled passengers and 20th airport in the world in terms of the number of handled ATMs (ATW, 2016).

The methodology used to develop the simulation models presented below could be consulted in a previous paper by the author (Herrera, 2012). In order to show the application of simulation models, the next four examples are presented. In all cases, the potential benefits of incorporating new technologies or procedures to the AICM were estimated.

1) Effect on the aircraft movements performed when the takeoffs and landings are redistributed between two runways of the AICM

In this case, the effect of shifting the proportions of takeoffs and landings performed at the two runways of AICM is analysed. To do this, different proportions were established by each runway, and then using a simulation model the total number of operations performed for each case was estimated. Subsequently, the results were plotted to show the trends and to observe the proportion that gives the maximum value of operations processed. For this model a general purpose discrete event simulation software was used. The results are represented in a three-dimensional system (Figure 3).

Figure 3. **Operations processed according to the proportion of landings and takeoffs on the runways, for a daily operation between 07:00 and 24:00**



The percentage of landings on the runway 05 left (05L) is represented in the Y-axis, the takeoffs percentage of the same runway on the X-axis, and the total operations processed in the two runways on the Z-axis. Although the percentages of takeoffs and landings on the runway 05 right (05R) are not indicated in this figure, their values are implicit in those assigned to runway 05L. When this model was developed (in 2003) the real proportions of takeoffs and landings on runways were: 82.3% takeoffs and 9.8% landings on runway 05L, and 17.7% takeoffs and 90.2% landings on runway 05R. At that time the AICM served approximately 748 operations between 07:00 and 24:00.

Under the theoretical condition of handling 100% of takeoffs on runway 05L and 100% of landings on runway 05R (lower right corner of Figure 3), i.e. the so-called segregated mode of operation, the AICM would be serving around 744 to 746 operations per day; these quantities are close to the maximum. However, according to the simulation model, the maximum value of operations (more than

750 operations, red area on Figure 3) could be achieved for a proportion of approximately 90% of takeoffs and 10% of landings on runway 05 left (or 10% of take-offs and 90% of landings on runway 05R).

2) Effect of intensive use of aircraft with greater capacity

The second considered case assumes that higher capacity aircraft is used at the airport to move the same number of passengers, i.e. there are effectively fewer ATMs than the airport needs to handle per day.1 In order to estimate the queue sizes and waiting times (maximum and average) on the runways a new simulation model was developed. The data to carry out the simulation model were obtained from *Servicios a la Navegacion en el Espacio Aereo Mexicano* (SENEAM).

The results of simulation are shown in Table 1, each value estimated is the average obtained from ten simulation runs. In absolute terms the reduction of the maximum queue sizes (two aircraft) is the main benefit, in this condition the reductions in average queues, and average and maximum waiting times are marginal (less than one unit). However, in relative terms, there are significant reductions in queue sizes (of around 19% in maximum and average), and in the average waiting time (15.4%), and the lowest benefit belongs to the maximum waiting time (6.5%). It should be noted how these benefits are obtained with a reduction in the runways' demand of almost 4%, and that the same number of passengers is transported.

Table 1. **Quality of service on AICM runways with ATR 42 or ATR 72 aircraft, for the interval between 06:00 and 24:00**

	Total operations	Queue size (aircraft)		Waiting time (minutes)	
ATR 42 operation		Maximum	Average	Maximum	Average
	788.90	10.80	1.32	11.86	1.82
ATR 72 operation	Total operations	Queue size (aircraft)		Waiting time (minutes)	
		Maximum	Average	Maximum	Average
	758.20	8.80	1.07	11.08	1.54
Comparative reduction	30.70	2.00	0.25	0.78	0.28
	3.89%	18.52%	18.99%	6.57%	15.48%

3) Effect of new technology to increase the capacity of airports with close-spaced parallel runways

The aircraft movement through the air generates wake vortices caused by the fuselage, empennage, landing gear, wings and engines. The vortices at the wing tips[2] are the main and most dangerous component of the wake turbulence. As a result of these vortices, fatal accidents in commercial and private aviation have been reported since 1972. ICAO has established mandatory minimum separations based on the category of vortices generated, which in turn depends on the aircraft maximum gross takeoff weight (ICAO, 1996).

Knowledge of wake vortex behaviour can increase capacity for airports with close-spaced parallel runways (runways separated by less than 2,500 feet) (Burnham et al., 2001). After several decades of research on vortex behaviour, wake transport over short times is well understood. In order to increase the capacity of runways with the use of this knowledge, new criteria have been suggested to reduce the current operational limits at airports. For example, it has been examined how the old practice of handling close-spaced parallel runways, as a single runway for the approximations by instruments, under certain conditions could be modified to permit a greater number of operations without affecting safety (Burnham, et al., 2001; and Vernon and Larry, 2008). The characteristics of the AICM runways indeed fit the definition of close-spaced parallel runways, because the runways of this airport have a separation of 1 017 feet.

Under favourable weather conditions the wake vortices usually weaken and dissipate in a period of one to three minutes. However, the weather conditions at different heights and the crosswind over the runways can disrupt this pattern. In order to counteract this drawback, patents and technological applications to monitor the wake vortices have been developed. For example, the Aircraft Wake Safety Management (AWSM) has been designed to detect and predict wake vortices (http://www.freepatentsonline.com/y2008/0030375.html). This system was developed by the American company Flight Safety Technologies (FST); the application possesses a set of ground sensors that monitor in real time the movement of the wake vortices generated by the aircraft. The system also includes monitoring equipment on-board the aircraft, weather information and forecast algorithms. The information obtained is used to continuously validate the predictions of the wake vortex behaviour in the air space of the airport. This technology has been tested at John F. Kennedy International Airport, Langley Air Force Base and Denver International Airport in the USA. The AWSM system monitors the airspace of the terminal area of the airport and, when it predicts the movement of the vortices outside the path of the aircraft, sets a "green light" condition, under which the flight controllers establish aircraft separation lower than those used under current conditions. In the event that dangerous vortices arise, the system establishes a "red light" condition, under which controllers apply current separation standards that are more conservative and, therefore, reduce the capacity of the airport (Herrera, 2008). The system however does not eliminate the safety risks related to vortices at airports. Therefore, its implementation does not automatically imply an increase in the runways capacity. This system determines in real time when it is operationally safe to reduce the mandatory separations and when it should be kept.

To estimate the effects of this technology in the AICM, it was assumed that the capacity of its runways is increased to 120 operations per hour, in accordance with the operational implications identified by the research of Vernon and Larry (2008). They established theoretically, that under certain operational conditions could be used a separation of 30 seconds between aircraft in close-spaced parallel runways, which was the maximum capacity that was used for this case. Using the capacity of 120 operations per hour, the value in the original model was adjusted (which handled 61 operations per hour) and it was determined under this new condition when the congestion problems initiate at the AICM (in which year the demand/capacity ratio is equal to 0.8) and the value of the corresponding amount of operations at runways.

For each level of demand ten simulation runs were performed. The values obtained were the magnitudes of queues and waiting times in the runways of AICM (maximum and average). The results are shown in Figures 4 and 5. In these figures the dates in which the different levels of demand will be reached are shown, the first corresponds to the values recorded in January 2011, the others are 60%, 70%, 80%, 90% and 100% of maximum capacity of the runways respectively. These dates were estimated according to a demand forecast.

The results show that if the new technology is applied to increase the capacity of the runways, the saturation is initiated until year 2036, unlike what was estimated with current capacity (congestion initiates in year 2015). In other words, with the new technology the congestion issues could be deferred an additional 21 years. In addition, the saturation with the new capacity occurs with almost twice the total current demand. According with the simulation model, with the current capacity the saturation begins with a daily demand of 1 171 operations and applying the new technology, it would begin with a daily demand of 2 303 operations.

It should be noted that the model used in this case only simulates the aircraft operation on runways, taxiways and apron, so it will be convenient to carry out new simulation models in order to evaluate other systems of the airport, for instance, the passenger and cargo terminals.

The advantages of increasing the capacity of the runways would not only occur in the future of the AICM operation, even with the demand presented in January 2011 benefits would be observed. For instance, it was estimated that with the capacity at that time, between 06:00 and 24:00, maximum queues of 10.8 aircraft and maximum delays of 11.86 minutes would occur. But with the capacity of 120 operations per hour, for the same interval, maximum queues of 6.1 aircraft and maximum delays of 4.08 minutes were estimated. The benefits of this technology only reflect the most favorable conditions that occur when there are not dangerous vortices.

Figure 4. **Evolution of service deterioration at AICM during the interval between 00:00 and 06:00, for a capacity of 120 operations per hour on runways**

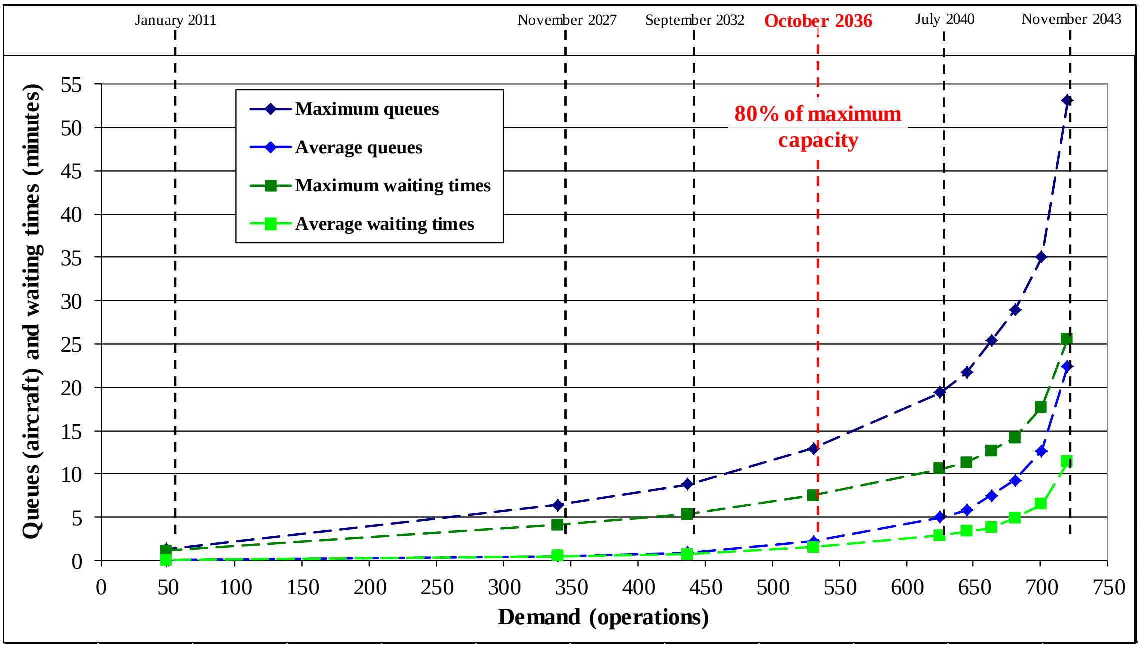
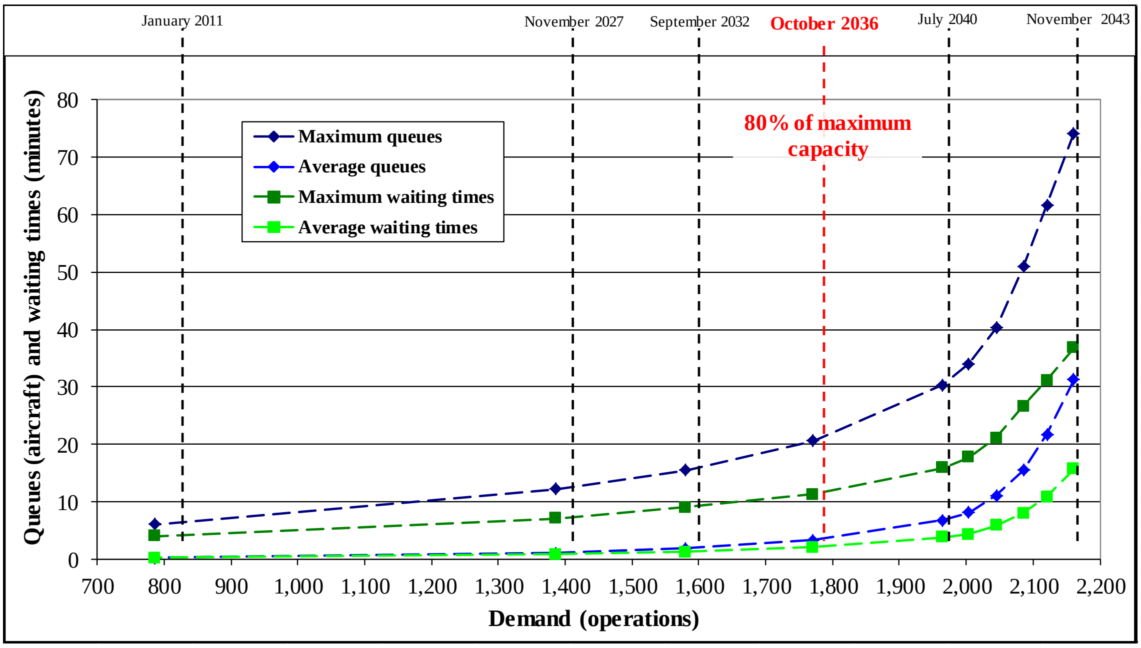


Figure 5. **Evolution of service deterioration at AICM during the interval between 00:06 and 24:00, for a capacity of 120 operations per hour on runways**



4) Potential benefits of applying a new policy to serve the aircraft at runways in order to reduce the passenger delays

In this case the impact of implementing a new policy to serve the operations at runways is estimated. This policy is different from the one currently applied world-wide (FCFS, first-come-first-served) and its purpose is to minimise the passenger delays. 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 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. 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 minimises such costs and 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 the solutions can be obtained in a short time. 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 minimise the operating costs and passenger delays (Herrera and Moreno, 2011).

Initially, 40 simulations were executed with the model, applying the current policy. The new strategy was subsequently evaluated, according to the proposal of Herrera and Moreno (2011) with 40 simulations performed. Afterwards the benefits in terms of waiting time reductions were determined comparing the current policy and the new strategy estimations.

In order to apply the new strategy, it was necessary to know for each aircraft in the queue its specific operation time and number of seats. The operation time for each aircraft was obtained using the information generated by the simulation model. This time is equal to the difference between entry time to and exit time from the runways. Although the number of seats in each aircraft can change, depending on the configuration of classes established by each airline, the values used here were typical figures established by aircraft manufacturers. The data used in the model reflect the operational conditions of the AICM in year 2011.

The results showed that by applying the new strategy, it is possible to reduce the daily waiting time in 10 763.2 passenger-minutes. Also, it was noted that the first six hours of operation of the AICM only contribute with the 0.46% of the benefits. During this interval queues of only two aircraft were observed. In contrast, after this period queues of two, three, four and five aircraft were estimated. Due to the reduced activity during the first six hours of operation at the AICM, a few queues were observed during this interval (1.38 average queues per day), and for this reason, only marginal benefits were obtained in that period. In comparison during the interval between 06:00 and 24:00, an average of 199.3 queues per day was estimated. If the benefits are expressed in annualised terms, the reduction of waiting time is equal to 65 476.3 passenger-hours.

The simulation models applied in the four cases presented before only provides part of the required information to cope with the problem of lack of sufficient airport capacity. Of course, other aspects must be considered in order to obtain a holistic solution. However, the potential of simulation models to establish guidelines that can contribute to the solution of the problem was shown.

Conclusions

In general, the solutions to cope with the congestion issues consist in reducing the ratio of demand to capacity. However, it may be controversial to decide to which part of the ratio must be given greater priority.

The simulation models could help to establish orientation guidelines to achieve a greater efficiency of the airport. For instance, it could be established with a simulation model the proportions of takeoffs and landings in order to maximise the operations in airports with several runways (case 1).

The use of aircraft with greater capacity that replaced to smaller aircraft could originate benefits in the operation of the airport, for instance, reducing the queue sizes and the waiting times. The reductions in some cases could be significant. The magnitude of the benefits depends on the amount of aircraft that were replaced and the interval in which they operate (case 2).

The application of a new technology to increase the capacity of the runways, in the best case, to 120 operations/hour would produce significant benefits in the operation of the AICM. Under this condition the congestion of the airport would begin until the year 2036, this means that the saturation issues could be deferred 21 years more (case 3). But it is important to emphasise that this result only reflects the most favorable conditions that occur when there are not dangerous vortices.

It was estimated that if a new proposal to serve the aircraft during takeoff and landing phases at the AICM runways is applied, it is possible to obtain reductions in the passenger delays (65 476.3 passenger-hours annually). In addition to the reduction of delays, there are other important benefits that could be obtained by applying the new strategy: reduction of the operating costs and reduction of greenhouse gas emissions. Base on the simulation model established here, it could be possible to quantify these benefits (case 4).

Finally, although the four cases described in the preceding section were considered in an independent way, they could be considered as an integral case, since they are complementary. In this way it is possible to obtain a greater efficiency for the airport facilities, benefitting passengers and airlines.

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Notes

[1] Assumptions: the airlines that operate aircraft ATR-42 at AICM change their fleet to ATR-72 aircraft. The ATR-42 aircraft has capacity to carry between 46 and 50 passengers. The enlarged model ATR-72 with greater capacity could transport between 67 and 74 passengers, depending on its configuration (http://www.atraircraft.com). For the purpose of the simulation it was assumed that the ATR-42 aircraft has capacity for 46 passengers, while the ATR-72 has capacity for 74 passengers. For the considered demand conditions (January 2011), there was no operations of ATR-42 aircraft between 00:00 and 06:00, however, for the interval between 06:00 and 24:00, 40 landings and 39 takeoffs of aircraft ATR-42 were performed, which would be equivalent to 25 landings and 24 takeoffs of ATR-72 aircraft.

[2] Wake vortices are disturbances caused by a pair of tornado-like counter-rotating vortices that trail from the tips of the wings. Aerodynamic lift, which causes an aircraft to rise into the air, is generated by the difference in air pressure as it moves across the upper and lower wing surfaces. As a wing moves through the air, low pressure is created across the curved upper wing surface and high pressure exists under the wing where the surface is fairly flat. This pressure differential creates lift, but it also causes the airflow behind the wing to roll into a swirling mass and form two counter-rotating circular vortices downstream of the wing tips. Source: https://www.nasa.gov/centers/dryden/about/Organizations/Technology/Facts/TF-2004-14-DFRC.html

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