SIMULATION OF THE MEXICAN AIRPORT NETWORK FOR ADDRESSING A GROUND DELAY PROGRAM

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ABSTRACT

Air traffic in Mexico has grown at a high pace, despite the economic downturns the country has suffered recently. In turn, Mexico City airport is located close to the centre of the city and is Mexico's busiest airport and is considered congested. One of the consequences of airport congestion are flight delays which in turn decrease costumer's satisfaction. Air traffic control has been using a ground delay program as a tool for alleviating the congestion problems, particularly in the most congested slots of the airport. This paper describes the application of a simulation model to analyse the effectiveness of the ground delay program. The use of the simulation model will enable the decision makers to analyse the effectiveness of the ground delay policy as well as to evaluate different policies for coping with the increasing demand in the Mexican network of airports.

Keywords: simulation model, airport capacity, flight delay, airports network

1. INTRODUCTION

Air transportation has grown very fast in the last century, especially in high and middle-income countries. Even in conservative scenarios, this growth is expected to continue in the future (EUROCONTROL, 2013; Campanelli et al., 2016). As a result, congestion problems and flight delays are becoming more acute in many airports. A flight is considered delayed when it arrives 15 or more minutes after the scheduled time (Federal Aviation Administration, 2009). According to the Federal Aviation Administration (FAA) in the United States, flight delays increased by more than 58 percent from 1995 until 2002 and cancellations by 68 percent (Nilim and El Ghaoui, 2004).

In airports with important capacity constraints, such as Frankfurt (FRA), London-Heathrow (LHR) and London-Gatwick (LGW), there is virtually no idle capacity available for growth and/or unscheduled flights such as general aviation, military or governmental flights (Bubalo, 2011). This is also the case of Mexico City International Airport, which was declared saturated between 7:00 am and 10:59 pm, observing on more than 52 occasions in 2013, at certain times, that operations in the Mexican air space exceeded the maximum number that can be attended per hour (SEGOB, 2014).

A study conducted in 2010 by the FAA estimates that flight delays cost the airline industry $ 8 billion annually, mainly for concepts such as increased crews, fuel and maintenance costs (Ball et al., 2010). The delays cost passengers even more, almost $ 17 trillion, according to the same author. Due to the high costs of delay, airlines and airport service providers are constantly looking to optimize flight times and resource utilization.

Traffic flow management initiatives can be used to control air traffic demand and mitigate demand-capacity imbalances. These can include ground stops, ground delay programs, rerouting, rescheduling, airborne holding, miles-in-trail restrictions (Chatterji and Sridhar, 2004; Ball et al., 2007; Swaroop et al., 2012; SESAR, 2012; Brunner, 2014). Applicable policies can be classified according to their time horizon (Terrab, 1990; Leal de Matos and Ormerod, 2000):

- *Long term* policies (several years) include the construction of new airports or the expansion of existing ones, as well as an improvement in air traffic control technologies which lead to time reductions.
- *Medium term* policies (up to 1 year) include modifications to and/or temporary redistributions of the flight planning, and changing departures to off-peak times to avoid periods of excessive demand.
- *Short term* or *tactical* policies (24 hours) as ground delay programs (GDP) are applied to diminish acute delay related costs and safety problems.

Implementation of ground or pre-departure delay programs (Luo and Yu, 1997; Dell'Olmo and Lulli, 2003; Agustin et al. 2010) is one of the most popular management initiatives throughout the globe: this corresponds to tactically match demand with capacity in the arrival airport by imposing a delay on the ground for a reduced number of flights at the airport of departure. Originally, it was implemented to avoid problems due to inclement weather. For example, in the US, when weather conditions deteriorate, the FAA can determine that part of the expected arrivals at an airport will exceed the airport's capacity and thus implement a GDP, specifying new arrival slot assignments for the affected set of flights (Luo and Yu, 1997). Besides the use of a

GDP to cope with bad weather, it can also be used to balance a congested airport's demand and capacity. This practice is theoretically cheaper, less polluting and less complicated, than allowing the aircraft to take off and put it on holding when it approaches its final destination (Guest, 2007). However, it is a disruptive tactic for air operators, whose schedules are set up with tightly connected operational resources and can therefore lead to excessive delays for the affected flights.
According to SENEAM, the Mexican air traffic control authority, the airport of Mexico City can only receive a maximum amount of 40 arrivals per hour (BNAmericas, 2014), so a GDP is currently used to reduce capacity problems during peak-hours. However, local airlines claim that this is causing them more inefficiencies, coupled with high costs and a declining reputation.

2. THE IMPORTANCE OF MEXICO CITY AIRPORT

The total number of operations in the Mexican air transport system reached more than 1,750,000 in 2016 (SCT, 1017a). Correspondingly, over 92 million passengers were transported in that year, which is an increase of 9.4% compared with the previous year (SCT, 2017b) while passenger flights constitute almost 90% of Mexico's air transport.
The domestic sector transported 53 million passengers (58% of the total) while international carriers moved 39 million passengers. Figure 1 shows the demand of the 9 existing commercial passenger airlines in Mexico in 2016. It can be noticed that the biggest national airlines in terms of transported passengers are Volaris, Interjet, Aeromexico, Aeromexico-Connect and VivaAerobus, which moved respectively 14.3, 11.1, 11.1, 8.5 and 6.2 million passengers. Together, they move over 95% of the flights served by Mexican carriers.

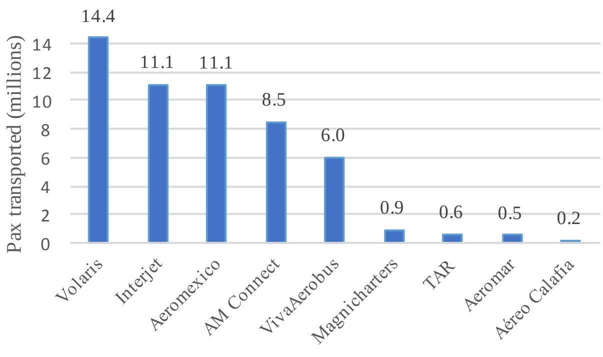


Figure 1: Passengers Transported by National Airlines in Domestic and International Routes in 2016

Mexico's flag carrier, Aeromexico, has had a steady growth since 2009, as can be observed in figure 2. However, Mexican low-cost carriers (LCC) are growing quite fast. In 2005-2006, Interjet, Volaris and VivaAerobus started operations, of which Volaris has presented the biggest growth until 2016. In 2016, the low-cost sector had already accounted for almost 80% of the market share. Other smaller airlines as Magnicharters and Aeromar have been operating for at least 15 years in the sector, although their market share is low and constant. Transportes Aereos Regionales (TAR) and Aéreo Calafia are two small LCC that just started operations three years ago.

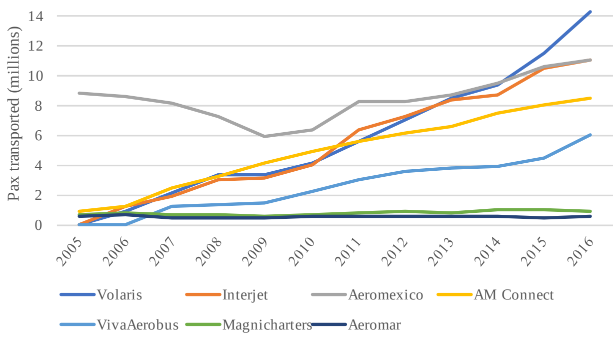
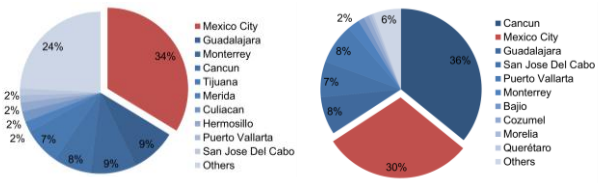


Figure 2: Main Development of Mexican Airlines Since 2005

Mexico has 76 airports, 58 of them are international airports and 18 national; in addition, there are 1,914 aerodromes registered in the country (SCT, 2017b). This places Mexico as one of the countries with the major airport network (CIA, 2017). Figure 3 presents the 10 top airports by passenger traffic within Mexico from January until May 2017. It can be noticed that Mexico City International Airport (IATA Code: MEX) moves 34% of the total domestic traffic of the country, followed by four other airports: Guadalajara (9%), Monterrey (9%), Cancun (8%) and Tijuana (7%), respectively. In the international context, Cancun International airport is a good competitor for Mexico City airport, moving 36% and 30% of the total, respectively. Considering both domestic and international passengers, MEX has a market share of approximately 32% of the total of transported passengers (SCT, 2017b), which makes it the busiest airport in the country. It also conforms, since 2003, the pillar of the Metropolitan Airport system, together with Queretaro, Puebla, Toluca and Cuernavaca.



(a) (b)

Figure 3: Air Passenger Traffic by Main Airports in Mexico, Jan-May 2017. (a) Domestic, (b) International (AICM, 2017)

The total number of operations (including less than 3% cargo flights and 8.5% of general aviation flights, mainly domestic) reached almost 450,000 in 2016, 73% of which corresponded to national flights and 27% to international ones (AICM, 2017).
Mexico City Airport is considered key for the development of the metropolitan region of Mexico city and the rest of the country. Recently, the government has announced the development of a new airport in Mexico

City which will have a final capacity of 120 mill pax/year. However, the first phase for this airport will not be operative until 2020. In the meantime, Mexico City as a destination is still growing and the country has also gained importance as a tourist and business destination. Since its important position in terms of number of operations as well as its functionality of the Hub operations of certain carriers, MEX reveals as an important node whose operation affects the complete national network of airports. Therefore, the understanding of efficient ways of managing the airport will affect not only the airport itself and the stakeholders that participate in it but also the complete national network.

3. LITERATURE REVIEW

Leal de Matos and Ormerod (2000) expose the application of operational research initiatives in the European Air Traffic Flow Management, detailing several of these strategies.

At the tactical level, the goal of GDPs (also called ground holding programs) is to avoid airborne delays by transferring them to the ground. The beginning of these policies goes back to 1973, when the oil crisis generated an increase in fuel costs that made air delays much more expensive. Consequently, the FAA adopted a policy to prevent the departure of an aircraft when its arrival at the destination airport could not be guaranteed and thus prevented the endless increase in the number of aircraft flying around the destination airport. Initially, the air traffic controllers made the decision based on their experience. However, advances in science have led to the development of operational research methodologies that allow finding an optimal or suboptimal solution (Agustin et al., 2010).

Most studies in the field focus on the optimal allocation of a GDP, as part of the Air Traffic Flow Management (ATFM) problem (Odoni, 1987; Andreatta et al., 1998; Leal de Matos and Ormerod, 2000; Inniss and Ball, 2004; Lulli and Odoni, 2007). In this sense, we can distinguish between the Single Airport Ground Holding (SAGH) problem, studied since the late 1980s (Andreatta and Romanin-Jacur, 1987; Terrab and Odoni, 1993; Richetta and Odoni, 1993; Dell'Olmo and Lulli, 1993), and the Multi Airport Ground Holding (MAGH) problem, studied since the early 1990s (Vranas et al., 1994; Richetta, 1995; Andreatta and Brunetta, 1998; Bard et al., 2001; Zhang et al., 2007; Glover et al., 2013).

Most studies model US applications, with congestion limited to airports. In-air congestion problems were not originally included in the analysis, because in the United States, where the problem was first studied, congestion only occurs at airports and not in the airspace. Early studies are generally deterministic (Terrab and Odoni, 1993), while recent studies, such as the ones from Mukherjee and Hansen (2007), Andreatta et al. (2011) or Agustin et al. (2012) consider the stochastic nature of the problem. Agustin et al. (2010) present an interesting and detailed review on optimization by mathematical programming models for air traffic flow management.

Since traffic flow management decisions are typically made 30 minutes to several hours in advance of anticipated congestion, the predictions are subject to significant uncertainty (DeArmon et al., 2008) and the solution to the described optimization problems are needed quickly. Documented solution mechanisms include branch and bound methods (Bard and Mohan, 2008), other exact methods (Andreatta et al., 1998), GRASP (Argüello et al., 1997), TSP (Vasquez-Marquez, 1991) and tailored heuristics (Luo and Yo, 1997), among others.

In addition, simulation has been used to represent and predict the air traffic system's capacity, demand and related congestion problems (Frolow and Sinnot, 1989; Winer, 1993) and to explore different strategies and system improvements (Frolow and Sinnot, 1989; DeArmon and Lacher, 1996). More recently, Fleurquin et al. (2013) used a simulation model to test a ground delay mechanism to a set of airports affected by weather perturbations. Delgado et al. (2013) used the FACET tool developed by NASA-Ames (Bilimoria et al., 2000) and the Airbus PEP program to assess cruise speed reduction for GDP.

This paper describes a simulation model to assess the current GDP in Mexico City. Stochasticity of the flight duration, on-time performance and turnaround times are included in the model to analyse how the effectiveness of the GDP is influenced by its parameters.

4. METHODOLOGICAL APPROACH

In this section, the proposed methodology is described together with the modelling approach for the different elements of the model.

Simulation using Discrete Event Systems (DES) is a special type of dynamic systems approach for modelling systems. The state of the system is a collection of variables that represent different values of the system under study. Hence the state of the system under study is defined by a combination of the values of the variables used. In the DES approach the "state" of these systems changes only at discrete instants of time and the term "event" is used to represent the occurrence of discontinuous changes at possibly unknown intervals (Flores de la Mota et al. 2017). Different discrete event systems models are currently used for specification, verification, synthesis as well as for analysis and evaluation of different qualitative and quantitative properties of existing physical systems such as manufacturing ones, port and airport systems.

In DES, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system; for this reason, this methodology suits the best for modelling a network of airports where the entities represent the aircraft that go from one place to the other following a specific sequence of steps where uncertainty affects mainly the speeds and processing times but not the structure of operations.

4.1. The Mexican network model

The simulation model used in this work corresponds to DES and was developed using the SIMIO software system (SIMIO 2017). SIMIO uses a process-object oriented approach which suits perfectly for the type of operations performed by the aviation industry, where everything happens at scheduled times and the control of uncertainty is one of the main goals of the operation.

The model involves aircraft moving between airports in a network of nodes connected by paths of a length proportional to the flight's travelling time. In the model only one destination is considered, which in this case is MEX; all direct flights to MEX and corresponding departure airports are included in the model. The first version of the model considers 98 departure airports, 26 carriers and 22 equipment codes; the latter are subdivided in medium, large and heavy aircraft, according to their maximum take-off weight (MTOW).

MEX airport has 56 direct boarding gates in two terminals, as well as 40 mobile contact positions in 6 remote platforms, making a total of 96 contact positions for air operations (SENEAM, 2015). Although flights are assigned to a specific terminal and/or contact position depending on the carrier and aircraft type, the model considers a total of 96 positions without distinguishing between carriers, aircraft type or terminal used.

The events in the simulation model are triggered by the information specified in the provided flight schedule, including origin airport, flight operator, aircraft type, departure time, arrival time and flight duration. Flights are generated in the model at the time of departure; the flight time to MEX is determined from the scheduled arrival time. Other data used by the model includes aircraft specific (for instance maximum take-of weight and wake category), airline specific (for instance on time performance, average arrival delay, type of operator) and airport specific (for example country of origin) information. Aircraft and airport specific data is used to be more accurate in the model logic, while airline data is used to be able to take into consideration the stochastic character of flight duration and delay.

4.2. Modelling the demand

Most of the data processing was done using the R software environment. The model was set up with flight information retrieved from OAG (2017), corresponding to the first week of 2013. The data includes a total of almost 200,000 registers, corresponding to the information of flights arriving to MEX airport in one or to flight legs. With information on the initial and last date where each flight is scheduled, and filtering the days of the week when a specific flight operates, daily flights were extracted from Jan 1 to Jan 8, 2013. Table 1 presents an example of the data used.

Table 1: Example of the Flight Data Used in the Model

Origin	Carrier	Equip	Flt No	Deptarture Time	Arrival Time
BJX	5D	ERJ	123	31/12/12 22:50	01/01/13 00:01
CUN	VB	733	3147	31/12/12 21:40	01/01/13 00:05
GDL	VB	733	2708	31/12/12 22:50	01/01/13 00:05
TIJ	Y4	320	816	31/12/12 20:44	01/01/13 00:05
PTY	CM	738	194	31/12/12 20:16	01/01/13 00:06
CJS	VB	733	3177	31/12/12 21:50	01/01/13 00:20
DFW	AA	M80	409	31/12/12 21:45	01/01/13 00:20
REX	VB	733	3219	31/12/12 22:55	01/01/13 00:25
CUN	VB	733	3149	31/12/12 22:25	01/01/13 00:50

4.3. Estimation of actual flight schedules

According to statistical information published by MEX (AICM, 2017), the number of flights in this airport have increased since 2013 with approximately 4% each year. While in January 2013 on average 490 flights were arriving at MEX, this number had increased to 575 in January 2017, registering a total increase of 17%. To take into account this increase and at the same time make the simulation model flexible enough to evaluate the GDP at different times, random flights were generated with the same origin, carriers, equipment and frequency distribution as registered flights. These additional flights were assigned to a specific hour-period according to the used time slots published by AICM (2017) for the first four months of 2017, and respecting the difference between different weekdays.

From Monday until Friday, an average of 1063 daily operations was registered in the analysed four-month period. Half of these, on average 531 flights, are assumed to correspond to arrivals, the rest to departures. On Saturday and Sunday, the number of daily arrivals diminishes with respectively 12% and 8% (See figure 4). Considering the weekend, the average was 1032 slots per day, thus approximately 516 arrivals and the same amount of departures.

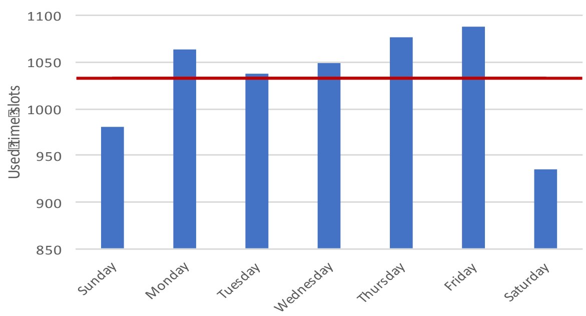


Figure 4: Average Used Time Slots in MEX per Weekday, Jan-Apr 2017

On the other hand, a variation of used slots according to the time of the day can be observed. Figure 5 presents the arrival slots for the less occupied and the busiest weeks in the analysed period. Analysis of the used AICM data indicated that the least busy week was just after the Eastern holidays, from April 23 to 29, with a total of 3437 arrivals for the whole week. The busiest week corresponded to March 19th to 25th in 2017; the total of 3932 arrivals in this week can be explained due to the spring break in the US (an increase of 14.4%).

Under the slot scheme presented by AICM (2013), that indicates a maximum number of 58 slots assigned to airlines and 3 to official aviation, but giving priority to passenger transport, it can be shown (see figure 5) that the airport is working at high capacity most of the day. Analysis of the graph suggests that when operations increase, slot use is increased early in the morning or late at night, when still some capacity is available. See for example the difference in blue and green lines for the periods between 04:00 and 06:00, or after 22:00.

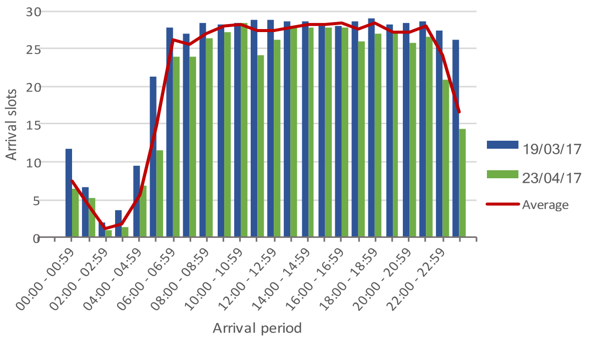


Figure 5: Used Time Slots per Hour in MEX, Jan-Apr 2017.

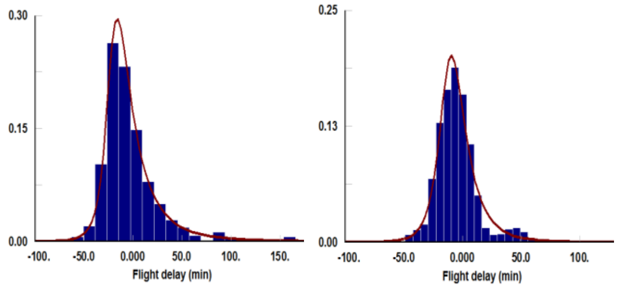
4.4. Analysis and modelling of flight times

The available departure and arrival times correspond to information scheduled before the flight takes place. Delay distributions were analysed from public flight information (Airportia, 2017) for the airlines flying to MEX in order to estimate in a more realistic fashion the arrival times. A total of 6221 flights operated between May 23 and June 10, 2017 were analysed.

As the highest share of analysed flights corresponds to Mexican airlines (26% Aeromexico, 23% low cost carriers), the delay distributions of these airlines were determined separately. All other airlines were grouped according to the continent where they were operating. Corresponding delay distributions were fitted using Stat::Fit®. In all cases, a Johnson S_U distribution could be fitted; this is a four-parameter family of distributions proposed by Johnson (1949) as a transformation of the normal distribution. Table 2 presents the values of the parameters for the fitted distributions. It is worth to note that negative values can occur, which correspond to flights arriving early; figure 6 presents two examples.

Table 2: Parameters for Fitted Delay Distributions, All Flights (Minutes)

Carrier	Johnson S_U Parameters			
	ξ	λ	γ	δ
Aeromexico	-22.0	18.7	-0.38	1.18
Aeromexico Connect	-23.0	18.9	-0.50	1.54
Aeromar	0.48	14.0	0.27	1.30
Interjet	-13.1	15.3	-0.49	1.23
Viva Aerobus	-34.0	12.0	-2.95	1.79
Volaris	-39.4	17.0	-1.38	1.47
Latin American carriers	-23.9	12.8	-0.85	1.14
North American carriers	-22.8	14.7	-0.87	1.07
European carriers	-16.1	15.7	-0.49	1.04



(a) (b)

Figure 6: Fitted Delay Distributions for (a) North American Carriers and (b) Interjet (min).

However, we perceived that, as the Johnson S_U distribution is unbounded, the use of the distributions presented in table 2 causes the model to sometimes estimate unrealistically large early arrivals. Also, flight delay for delayed flights was underestimated for all operators. To avoid these drawbacks, the data to be fitted was subdivided in two categories: on-time flights, i.e. flights being delayed less than 15 minutes and where both positive and negative delays can be observed due to randomness, and flights delayed more than 15 minutes due to a specific although not necessarily known reason. For on-time flights, most carriers or carrier groups could be fitted to a Weibull or gamma distribution. Only Viva Aerobus was fitted to a Johnson S_B distribution (see Table 3). The fitted distributions resulted to be rather symmetric, with mean values around -12 (aircraft arriving 12 minutes early) and standard deviations around 14 minutes. The high standard deviation explains the fact that, on long flights, there are planes arriving up to 60 minutes early. Our findings are consistent with the flight distributions used for example by Dorndorf (2016) and Pérez-Rodríguez (2017).

Table 3: Parameters for Fitted Delay Distributions, On-Time Flights (Minutes)

Carrier	Gamma Parameters			
	Location	Shape	Scale	
Aeromexico	-249	202	2.15	
Aeromexico Connect	-64	11.1	4.33	
Volaris	-62	6.85	6.14	
	Weibull Parameters			
	Location	Shape	Scale	
Aeromar	-43	3.82	43.1	
Interjet	-62	4.83	58.6	
Latin American carriers	-55	3.42	45.9	
North American carriers	-63	3.8	56.6	
European carriers	-52	3.06	46.5	
	Johnson S_B Parameters			
	ξ	λ	γ	δ
Viva Aerobus	-39.5	74.8	0.348	1.38

For delayed flights, a second distribution was fitted using the same logic as explained above. In all cases, a Weibull distribution was fitted for late flights (see table 4).

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Table 4: Parameters for Fitted Delay Distributions, Late Flights (Minutes)

Carrier	Weibull Parameters		
	Location	Shape	Scale
Aeromexico	15	0.82	23.2
Aeromexico Connect	15	0.67	20.9
Aeromar	15	1.36	19.3
Interjet	15	1.35	28.9
Viva Aerobus	15	1.39	27.3
Volaris	15	1.05	37.0
Latin American carriers	15	1.43	38.3
North American carriers	15	0.92	30.3
European carriers	15	0.95	34.7

Having estimated distributions for both on-time and delayed distributions, in-flight delay was randomly assigned in the model to each incoming flight, according to the corresponding on time performance data (SCTb, 2017; BTS, 2017; Flightstats 2017). Published percentages of late flights (delays of more than 15 minutes) range from 3% for AVIANCA PERU to 28.03% for AVIANCA. Corresponding average arrival delay ranged from 30 minutes for Interjet to 71.3 minutes for Delta Airlines. The logic used in the simulation model to assign flight delay is presented in figure 7.

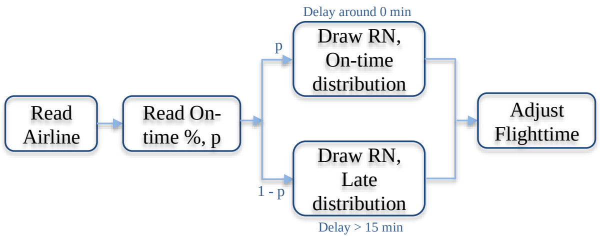

Figure 7: Assignment of Flight Delay in the Simulation Model.

As an example, Aeromexico Connect presented 76.5% of on-time flights according to the reviewed information. This means that the simulation model will assign a random positive or negative delay < 15 min, drawn from the corresponding gamma distribution in table 3 and figure 8, to 76.5% of the incoming flight operated by Aeromexico Connect. The other 23.5% of flights will have a randomly assigned delay > 15 min, drawn from the corresponding Weibull distribution in table 4 and figure 9.

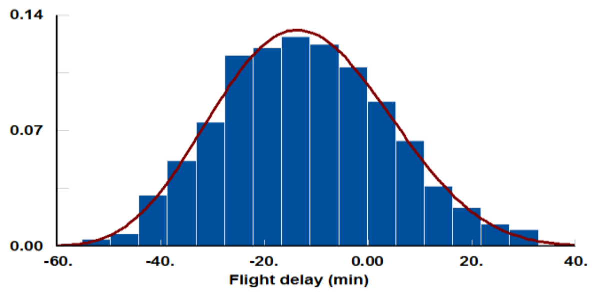

Figure 8: Fitted On Time Distribution for Aeromexico Connect

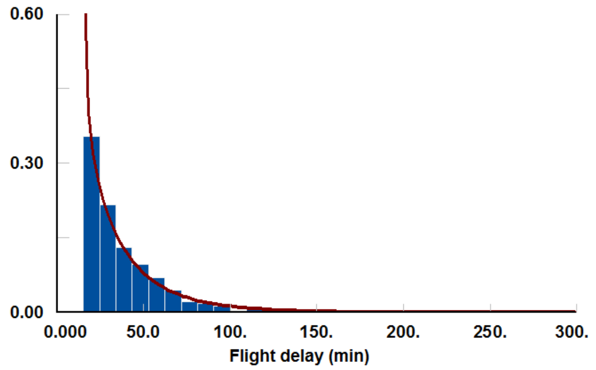

Figure 9: Fitted Late Distribution for Aeromexico Connect

4.5. Simulation of turnaround times

In order to represent the time that a plane is using the assigned gate, turnaround times were estimated from public flight data available from January 26th to February 15th, 2017. Turnaround times depend on several variables, among which the type and size of the aircraft, the degree of saturation and the type (hub or non-hub) of the arrival airport and airline strategies (full-cost or low cost carriers) (Kolukisa, 2011) and its determination is of vital importance to simulate the arrival and departure process correctly.

To obtain an estimated turnaround distribution, different aircraft types were selected for Mexican carriers, typically of the type flying to MEX airport. Through analysis of the aircraft's history, turnaround times were obtained for the Mexican flag carrier and for the 3 major low cost carriers. Airbus 320 and 321 (IATA codes 320 and 321), as well as Boeing 737-700, 737-800, 777-200 and 787-800 (IATA codes 737, 738, 777 and 788 respectively) were included in the analysis. Of the previous, only 777 and 788 are heavy aircraft; the rest are classified as aircraft with wake category M (*medium*).

The fitted distributions are presented in table 5. It can be observed that for medium size aircraft, the turnaround time was generally between 30 and 165 minutes, with distribution mode around 85 minutes. All analysed medium aircraft presented a similar pattern and the corresponding data was merged to obtain a generic loglogistic turnaround time distribution for other medium aircraft not considered in the analysis. For heavy aircraft, mean turnaround times were around 250 minutes (4.2 hours); variability seems so increase with aircraft size, presenting ranges from 2.8 to 5.3 hours for 787 aircraft and 2 to 7 hours for 777 aircraft. As less than 4% of the flights in the analysed flight schedule correspond to heavy aircraft, available information was insufficient to obtain more detailed results. The distribution obtained for Aeromexico's 787 aircraft was used for aircraft with wake category *heavy* when no distribution could be obtained.

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Table 5: Proposed Distribution for Turnaround Times (Seconds)

Carrier	Aircraft	Turnaround Time Distribution (s)
Aeromexico	737	1980+7920*Beta(3.18, 4.18)
Aeromexico	738	3420+LogLogistic(3.97, 3030)
Aeromexico	777	8040+Weibull(1.78, 8640)
Aeromexico	788	8220+Weibull(4.52, 6760)
Interjet	320	2040+Lognormal(7.68, 0.508)
Interjet	321	3360+8040*Beta(3.59, 6.72)
Volaris	320	4140+ LogLogistic(1.95, 1480)
Volaris	321	3540+7070*Beta(1.79, 4.88)
Generic	Medium	1980+LogLogistic(3.66, 3390)

4.6. Verification phase

To analyse if the model is working as intended, and to ensure that it produces satisfactorily accurate and consistent results, it was verified thoroughly. Verification activities include comparison of used gates with published slot usage information, verification of the average arrival delay simulated with the proposed distributions and review of the results of simulation trials to check if calculated quantities correspond with the expectations. After the verification was performed and the model was ensured to behave qualitatively according to real reported results we continued to the next phase.

To verify the delay distributions used for late flights, mean and standard deviations were determined for the corresponding Weibull distributions to determine the simulated average arrival delay for all airlines flying to MEX airport. Its value ranged from 32.7 to 52.3 minutes. Although slightly underestimated, the simulated average arrival delays are in the expected range.

5. SCENARIOS AND FINDINGS

The simulation model was used to evaluate the current GDP at MEX airport. When the GDP is not active, the simulation model processes incoming flights on a first come first served base and on-time flights are processed immediately.

In its current form, when delay information on departing flights and/or meteorological conditions suggests that the maximum airport capacity will be reached in the following hours, MEX airport authorities decide to implement the GDP and aircraft coming from nearby airports are delayed by a fixed 15 minute-period to try to decrease the level of saturation. At present, the GDP does not apply to flights coming from abroad. Apparently, the current GDP is based on experience and there are no clear rules on how to implement it. As the airport saturation level in MEX persists to date, changing the GDP parameters might improve its effectiveness.

Two basic scenarios were analysed: the base case considers the current situation, were aircraft are included in the GDP depending on their origin, while the other scenario considers the selection of included aircraft based on their flight time. For both scenarios, 15 different thresholds were tested: the objective pursued was to identify the sensibility of the system to the modification of the threshold value where the GDP program is triggered. Each experiment is executed for a period of seven days; 10 replications were made in all cases. Specific parameters for the simulation runs are:

- *Airport arrival capacity or acceptance rate* where the GDP starts to operate: In our model, this limiting capacity is fixed during the simulation run, as it depends on the saturation of the airport; it varied from 25 to 40 arrivals per hour. However, when a GDP program is due to weather conditions, this value could change during its implementation (see for example Ball and Lulli, 2004).
- *Type of GDP*: The base case considers only flights departing from Mexican airports and operated by Mexican carriers to be included in the program (scenario 1). The alternative scenario includes in the GDP flights with less than 2h of programmed flight time (scenario 2). Longer flights are not included as they are assumed to arrive when the saturation crisis might be solved already.
- *Imposed delayed time*: Currently, the model considers imposed delays in the departure airport in blocks of 15 minutes; however, this can be changed in future runs.

Figure 10 presents how the GPD is implemented in the simulation model. Note that a specific aircraft can enter the GDP program more than once. If desired, a maximum number of delays can be specified in the model, however this has not been evaluated yet.

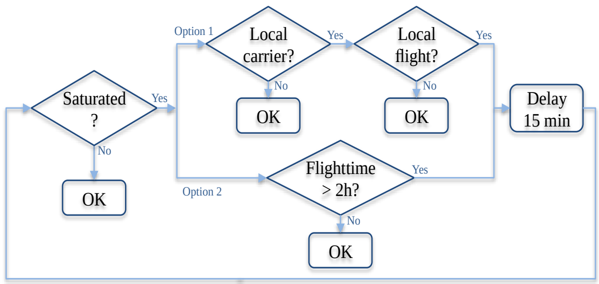

Figure 10: Simulation Logic for Implementation of the Ground Delay Program

Figure 11 displays the simulated total percentage of delayed flights, both including GDP and flight delays, as a function of limiting arrival capacity. It can be observed that for triggering airport arrival rates above 34, the total percentage of delayed flights is maintained almost constant for both scenarios; its value is around 26.7%, which is the same value as the percentage of flight delays. In other words, in this case the implementation of a GDP does not have a significant influence on the percentage of total delayed flights. However, for small limiting arrival rates, such as 25 arrivals per hour, this percentage increases to 40% for scenario 2 and up to 44.5% for scenario 1. These high percentages are due to the long periods were aircraft are obliged to remain on the ground.

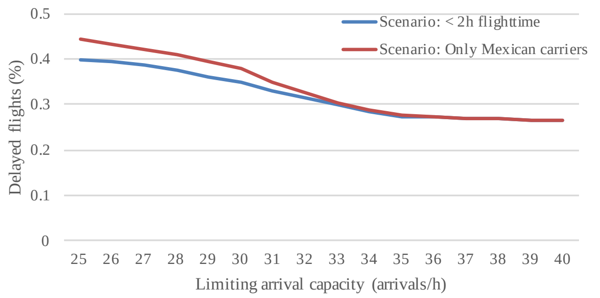

Figure 11: Average Total Delay (Sum of GDP and Flight Delay) as a Function of Limiting Arrival Capacity

Figures 12 and 13 show, respectively, the simulated average GDP delay imposed per aircraft (in minutes) and number of aircraft affected by the ground delay program in terms of limiting arrival capacity, for both the scenario where only Mexican carriers are included in the GDP and the one where flights are included depending on whether their flighttime is less than 2 hours. They indicate, respectively, that the average delay imposed on an aircraft due to the implementation of the GDP varies from around 70 minutes when the GDP is activated at 25 arrivals per hour, to around 20 minutes at 40 arrivals per hour. The number of affected aircraft increases dramatically when the GDP is triggered at lower arrival acceptance rates. The proposed value of 34 arrivals per hour as the limiting airport capacity would affect 200 to 300 aircraft in one week, depending on which scenario is chosen.

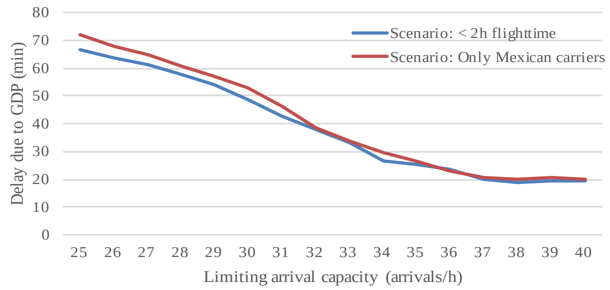

Figure 12: Observed Average GDP Delay per Aircraft (min) as a Function of Limiting Arrival Capacity

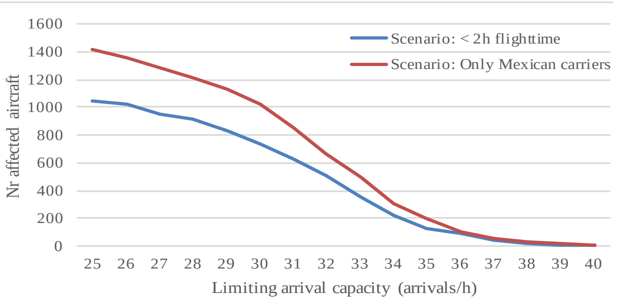

Figure 13: Observed Number of Aircraft Affected by the Ground Delay Program

Based on the previous information, preliminary simulation results suggest the following:

- A GDP at MEX airport seems to work best for acute congestion problems. Since not all aircraft are included in the program, under conditions of severe and chronic congestion, aircraft continue to arrive despite the GDP, which can increase total delay unacceptably for affected flights. In this case, cancellation of flights in combination with the GDP could be an option.
- As aircraft arrive on average about 10 minutes early, delaying an aircraft in a GDP by a 15 minute-period might not be effective, as this delay can be recovered during flight time.
- If the GDP is implemented with smaller limiting airport capacities (e.g. from 30 arrivals per hour), peaks can be observed during the simulation runs in the number of flights arriving per hour. This can indicate a shift in the peak: as more GDP delays are imposed, the saturation seems to decrease in the aimed peak; however, if after some period, for example 1 hour, this apparently lower saturation allows all delayed aircraft to take off, a new saturation peak can be observed in the next two hours, when all these aircraft arrive.
- Starting a GDP at limiting arrival capacities of 37 or more arrivals per hour does not seem to be effective, since almost no aircraft would be included in the program and saturation levels will not be improved.
- If the GDP is activated when 34 arrivals per hour or more are observed, the average percentage of delayed flights (including both GDP delays and flight delays) seems to be maintained almost constant (see figure 11). However, although the number of delayed flights does not increase, the affected flights are delayed by longer time periods. Although not explored at the time, in a future research a fuzzy logic rule can be implemented to select the triggering arrival capacity in the operation of the GDP.
- The scenario in which flights are imposed a GDP delay based on their flight time, seems to be more effective than when only Mexican carriers on flights from Mexican airports are considered. However, the differences between both scenarios decrease with the increase in limiting airport capacity.

6. LIMITATIONS AND FUTURE WORK

The conclusions that were drawn in this study correspond to a first version of our simulation model. As we found some limitations in the available data, our conclusions should be considered as preliminary. Examples of limitations are:

- On line statistics change considerably from month to month. On the other hand, values published by different sources do not necessarily correspond to each other.
- Availability of information in Mexico is more limited than is the US or European aviation

networks, so several parameters had to be estimated. Using a larger amount of data, model performance is expected to increase.

- As the departure time and therefore the use of airport facilities depends to a large extent on the turnaround time of the aircraft when it arrives at MEX, a deeper analysis of turnaround times in terms of carrier, aircraft type, arrival airport and flight route is desirable.
- For the moment, the model does not consider the situation in which carriers do not respect the capacity of the 58 assigned slots for landings and take-offs.

Future work includes a deeper analysis of model input data and an improved representation of its stochastic aspects, especially in relation to different causes of delay, updated flight information and probability distributions for delay and turn-around times per aircraft, airline and destination. The model's accuracy can also be improved by taking into account more detailed information on actual airport operations in MEX, such as specifying the arrival terminal and/or specific contact positions depending on the carrier and the type of aircraft.

7. CONCLUSIONS

Mexico City International Airport is a critical facility for the development of different aspects in the country, ranging from tourism to business. In this paper, we present a discrete-event-based simulation model that we used to analyse the effectiveness of the ground delay program currently imposed by Mexican airport authorities as a measure to address capacity imbalances. Stochasticity of the flight duration, on-time performance and turnaround times are included in the model to analyse how the effectiveness of the ground delay program is influenced by its parameters.

Simulation runs over several scenarios suggest that by activating the ground delay program with 34 arrivals per hour combined with a decision rule on which aircraft to include in the program could decrease its impact on carriers to some extent. In a future study, the stochastic nature of delays and turnaround times will be addressed more deeply, and different types of delay affecting MEX airport congestion will be included in the study.

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