Analysing the Decision-Rules for a Ground Delay Program: Mexican Airport Network

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***Abstract*— Mexico City airport is located close to the center of the city and is Mexico's busiest airport which 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 uses a model-based approach for analyzing the effectiveness of the ground delay program and rules. The results show that however the rules applied seem efficient, there is still room for improvement in order to make the traffic management more efficient.**

Mexico City Airport; airport capacity; airtransport management; airtraffic

I. Introduction

Air transportation has grown very fast in the last century, in conservative scenarios, this growth is expected to continue in the future ([27]; [20]). As a result, congestion problems and flight delays are becoming more severe in many airports. A flight is considered delayed when it arrives 15 or more minutes after the scheduled time [28]. 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 [43]. In the respect of European airports, some airports have severe capacity constraints, like London-Heathrow (LHR) or London-Gatwick (LGW) where there is virtually no available capacity for growth and/or unscheduled flights such as general aviation, military or governmental flights [19]. Furthermore, 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 [11]. The delays cost passengers even more, almost $ 17 trillion, according to the same author.

In the Americas, one interesting case is 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 according to SENEAM, the Mexican ATC [50].

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 ([22][12][54][52][17]). Applicable policies can be classified according to their time horizon ([55][39]):

- 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 ([26][1]) 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. This practice is theoretically cheaper, less polluting and less complicated, than allowing the aircraft to take off and put it on holding trajectory when it approaches its final destination [34]. 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 airport of Mexico City can only receive a maximum amount of 40 arrivals per hour [16], so a GDP is currently in place for reducing capacity problems during peak-hours. However, local airlines claim that this is causing them more inefficiencies, coupled with high costs and a declining reputation.

II. Mexico City Airport Importance to the Network

The total number of operations in the Mexican air transport system reached more than 1,750,000 in 2016 [48]. Correspondingly, over 92 million passengers were transported in that year, which is an increase of 9.4% compared with the previous year [49] 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.

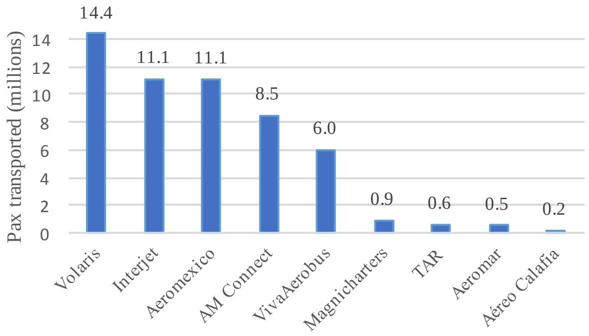

Figure 1. Passengers Transported by National Airlines in Domestic and International Routes in 2016

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 faster than that. 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.

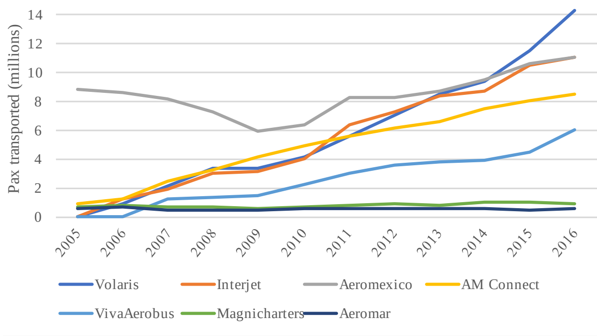

Figure 2. Growth of Mexican Airlines Since 2005

Mexico has 76 airports, 58 of them are international airports and 18 national; in addition, there are 1,914 aerodromes registered in the country [49]. This places Mexico as one of the countries with the major airport network [21]. 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 [49], which makes it the busiest airport in the country.

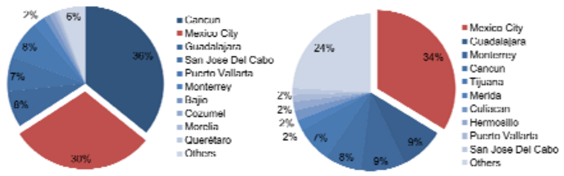

Figure 3. Air Passenger Traffic by Main Airports in Mexico, Jan-May 2017. (a) Domestic, (b) International (AICM, 2017)

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 strategic position in terms of connectivity, 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. For this reason, understanding efficient ways of managing the airport will affect not only the airport itself and the stakeholders that participate in it but also the complete country network.

III. LITERATURE REVIEW

One extensive work is the one from [39] where they expose the application of operational research applications in the European Air Traffic Flow Management.

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, 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 [1].

Most studies in the field focus on the optimal allocation of a GDP, as part of the Air Traffic Flow Management (ATFM) problem ([45][6][39][35][40]). In this sense, we can distinguish between the Single Airport Ground Holding (SAGH) problem, studied since the late 1980s ([9][56][47][26]), and the Multi Airport Ground Holding (MAGH) problem, studied since the early 1990s ([58][46][7][14][33][61]).

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 [56], while recent studies, such as the ones from Mukherjee and Hansen [42], Andreatta et al. [8] or Agustin et al. [2] consider the stochastic nature of the problem. In [1]present a 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 [24] and the solution to the described optimization problems are needed quickly. Documented solution mechanisms include branch and bound methods [13], other exact methods [6], GRASP [10], TSP [57] and tailored heuristics [41], among others.

In addition, simulation has been used to represent and predict the air traffic system’s capacity, demand and related congestion problems ([32][59]) and to explore different strategies and system improvements ([32][24]). More recently, [29] used a simulation model to test a ground delay mechanism to a set of airports affected by weather perturbations. In [25], they used the FACET tool developed by NASA-Ames [15] and the Airbus PEP program to assess cruise speed reduction for GDP.

In most of the research done so far, the problem was reduced to a concept of network and demand in which most of the provided solutions had a deterministic nature. However, as it has been discussed by some authors, the implementation of those deterministic solutions are in most of the cases unfeasible due to the stochastic nature of reality. This paper presents a novel approach using a discrete-event based simulation model to assess the current rules of GDP in Mexico City under uncertain conditions. Stochasticity of the flight duration, on-time performance and turnaround times are included in the model to make it as realistic as possible providing more help in giving light of the efficiency of the GDP program in place.

IV. METHODOLOGICAL APPROACH

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 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 [31]. 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. The following are the most relevant elements of the model

A. Airport network

The simulation model used in this work corresponds to DES and was developed using SIMIO software system [53]. SIMIO uses a process-object oriented based 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 representing airports located over a GIS layer. They are 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. Figure 4 illustrates the GIS over which the network of airports has been developed.

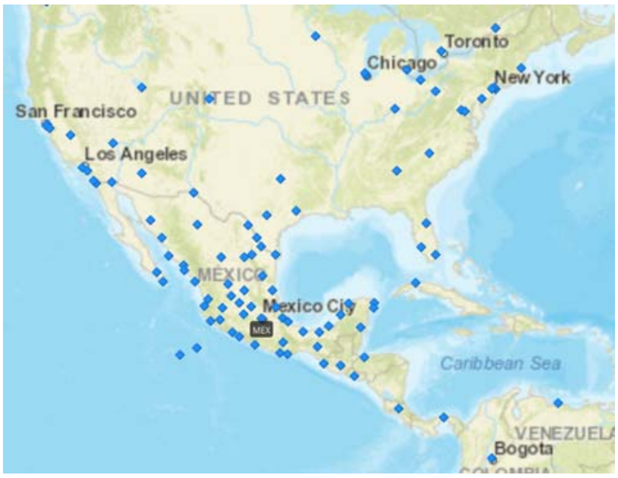

Figure 4. Airport Network of Mexico

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 [51]. 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 aircraft are generated from the 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.

The model was set up with flight information retrieved from OAG [44], 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 two flight legs from Jan 1 to Jan 8, 2013.

B. *Flight schedules*

According to statistical information published by MEX [4], 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 [4] for the first four months of 2017, and respecting the difference between different weekdays.

Figure 5 illustrates the amount of slots used in the flight schedule of the week under study.

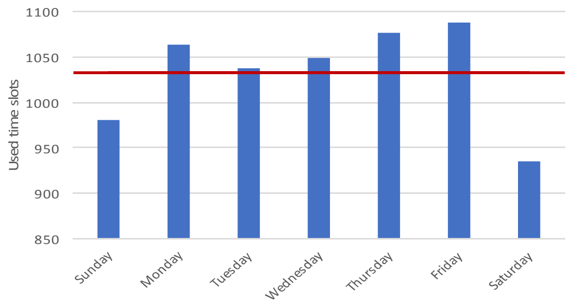

Figure 5. Average Used Time Slots in MEX per Weekday, Jan-Apr 2017

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 analyzed period, this was also taken into consideration for the development of the flight schedule used.

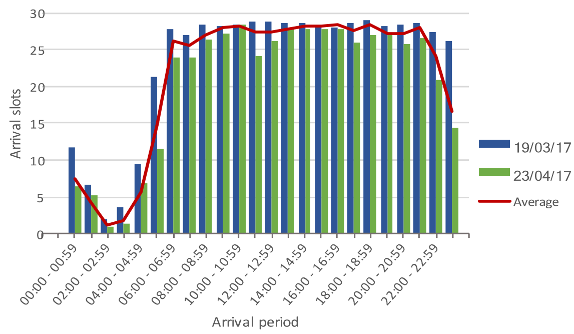

Figure 6. Used Time Slots per Hour in MEX, Jan-Apr 2017.

C. *Flight times*

The available departure and arrival times correspond to information scheduled before the flight takes place. Delay distributions were analyzed from public flight information [5] 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 analyzed.

As the highest share of analyzed 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 also and the probability distributions used for the actual flight time.

Having estimated distributions in-flight delay was randomly assigned in the model to each incoming flight, according to the corresponding on time performance data ([49][18][30]). 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; for a more detailed information of these calculations, we refer the reader to check [60] .

D. Turnaround times

To obtain an estimated turnaround time (TAT) 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 I. These TATs were used to model the time the capacity of MEX is seized thus it is possible to simulate also departures.

Table I. Probability Distributions Used

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)

These were the main inputs used for the network of airports and in the following section the scenarios, analysis and findings are presented.

V. SCENARIOS

We study the impact of new policies on the GDP, four different independent scenarios for selecting which flights will be included in the GDP were considered:

1. GDP to only flights departing form Mexican airports, operated by Mexican airlines (MEX)
2. GDP to only flights departing from international airports, operated by international airlines (INT)
3. GDP to flights with an expected flight time less than 2 hours (<2h)
4. GDP to flights with an expected flight time equal or higher than 2 hours (>2h)

The impact of these scenarios was studied also by considering different values of the arrivals per hour (Arr/hr) that will trigger the GDP. The expectation is that low Arr/hr values will result in more affected aircrafts by the GDP, as it will be more likely to find a state in the system where the limit is reached.

The domain of Arr/hr is [25..40] incremented in each experiment by 1. The 40 Arr/hr represents the current limit of arrivals per hour imposed by the airport. Therefore, the combination of these 16 values with the 4 scenarios considering policies for the GDP resulted in a total of 64 experimental points tested for this initial part of the study.

There are key variables to be considered in the design of experiments: the revision period factor (Rt) and the time allocated per delay (Dt). The Rt represent the units of time the air traffic controller will measure the number of flights that reached the airport on the last Rt units of time. In this way, air traffic controllers (ATC) will only need the information of arriving flights of the last Rt minutes, instead of a complete dataset of all the arrivals in a period higher than Rt. The Dt corresponds to the amount of delayed time applied by the GDP.

If Rt < Dt then some flights could be delayed more time than required, as a quick revision due to T could identify a reduced airport workload before the delayed time finishes. On the contrary, if Rt > Dt, new information about the state of the workload at the airport will not be considered every time a delay is finished, so it is likely that the flight will suffer an additional delay as no new information is available. For the experiments, the following domain was explored in the experimental design:

Rt = {15, 30, 45, 60)

Dt = {5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60}.

For evaluating the combinations of Rt and Dt, we used three different values for Arr/hr resulting in a factorial design of 144 experimental points. Thus, a total of 64 + 144 = 208 experimental points were tested. Each experiment had 100 simulation replications with a warm-up period of 8 hours using the Simio, version 9.147. Total simulation time per run was equal to 185 hours.

The three principal responses that were measured by experiment were the following:

- Average time a flight was delayed by the GDP
- Number of instances that GDP was applied overall
- Number of aircraft delayed, on average, by the GDP

VI. RESULTS

Figure 7 shows the impact of using different policies to select the flights that will be included in the GDP. These results suggest that the impact of each policy does not entirely depend on the percentage of flights selected in each policy, as not all the lines follow the same shape. For instance, when selecting the flights with more than 2 hours of flight time to be included in the GDP, the total number of instances that the flights are delayed with a very tight limit (25 arrivals/hr) is bigger than when selecting the flights with less than 2 hours of flight; however, when we compare these two scenarios in a less constrained GDP (e.g., 33 arrivals/hr.), the ">2h" scenario results in a smaller number of instances of GDP than the "<2h" scenario. This behavior might provide light in the best management of the GDP under diverse conditions.

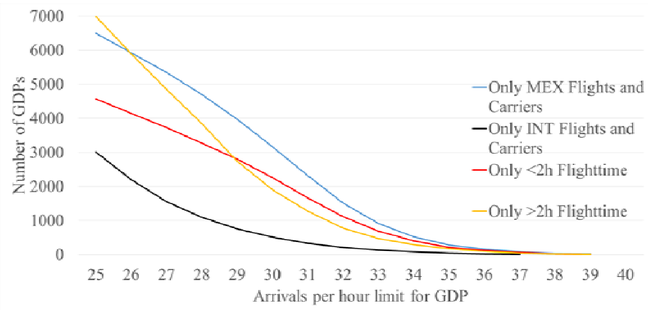

Figure 7. Number of instances that the GDP was applied in total depending on the limit imposed to start the GDP

The effect of different combinations of Pt and Dt is shown in Figure 8, where it can be clearly seen that applying a high delay time (Dt) will result in less number of GDPs because the probability of having a highly congested airport after a very long ground delay is low. On the other hand, considering a shorter Rt will result in a lower probability of constantly finding a congested airport since a short Rt allows to rapidly accommodate changes in the airport congestion. This situation might sound good, however, it might imply a higher workload for ATCs.

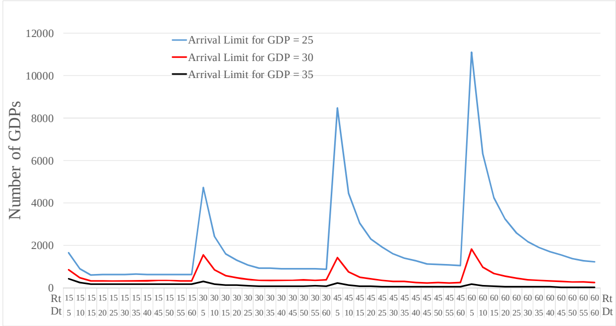

Figure 8. Number of instances that the GDP was applied depending on combinations of Rt, Dt and Arr/hr

Figure 9 illustrates that longer Rt and Dt values will result in longer accumulated delays and a tighter GDP (e.g., Arr/hr = 25) will be more sensitive to changes in these values.

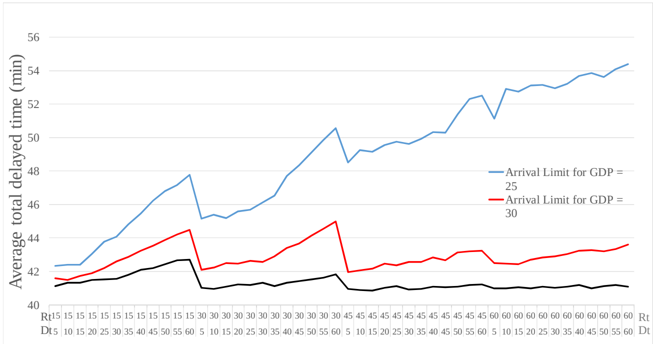

Figure 9. Mean time that a flight was delayed depending on combinations of Rt, Dt and Arr/hr

Figure 10 presents results regarding the combined effect between Rt and Arr/hr. As contrary to other measurements, the effect of Rt on the average number of affected aircraft is completely dependent on Arr/hr. For instance, when Arr/hr = 25, i.e. a tightly imposed GDP, the number of affected aircraft increases as Rt increases; however, when Arr/hr = 35, i.e. a loose GDP, the number of affected aircraft decreases as Rt decreases. In the case of a tight GDP, the system will quickly identify a congested airport in high Rt values. In the case of a loose GDP, it will be more difficult to find a big accumulation of arrivals in a longer time-span than it will be to find the same congestion in a shorter time-span.

Notably, Figure 10 also shows how the average number of affected aircraft when Arr/hr = 30 does not monotonically increase or decrease as Rt increases. This behavior shows that the interaction between the factors Rt and Arr/hr is a very strong interaction and needs further study.

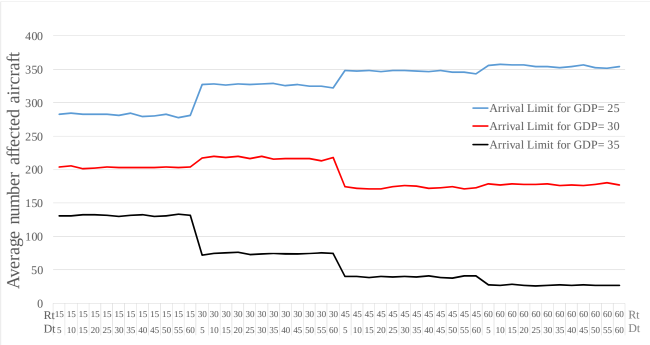

Figure 10. Average number of aircraft affected by the GDP depending on combinations of Pt, Dt and Arr/hr

VII. Conclusions and Future Work

Mexico City International Airport is a critical facility that is considered strategic in the continent as a potential Hub from airlines flying from south to north or vice versa. The airport is part of a network of airports in the country, and itself as a node in the network is very sensitive, since its correct performance affects the whole network. In this paper, we present a discrete-event-based simulation model for analyzing different policies for the GDP applied in Mexico. The objective is to provide light in the values that work best under diverse conditions. We identified, that on the one hand the policy of delaying different traffic provides better or worse results depending on the arrivals per hour in operation. The results suggest that under tight limitations, it is better to apply the GDP to the airlines with long flights, this can be the situation under adverse weather conditions. On the other hand, we also identify the dependency between delayed flights with the Dt, in which we could identify that under tight restrictions, it is necessary to reduce the Dt and Pt to avoid he increase of affected aircraft. In general terms we can conclude that due to the dynamic nature of the system, it is necessary to have a more flexible GPD that self-adapts to the current conditions of the network.

As a future work, the authors will investigate the aforementioned dependencies and will consider policies that consider the flight schedules in order to replicate the decision-making process of ATCs.

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