Adopt an airport project

Philadelphia Airport (PHL)

Eduard Algar Creus
eduard.algar@estudiantat.upc.edu

Martí Payà i Majó
marti.paya@estudiantat.upc.edu

Abstract: study of the impact generated by the implementation of different ATFM regulations to PHL airport.

Keywords:

- *Hstart – regulation starting time*
- *Hend – reduced capacity ending time*
- *Hfile – regulation setting time*
- *HNoReg – regulation ending time*
- *AAR – airport acceptance rate*
- *PAAR – reduced airport acceptance rate*
- *RBS – ration by schedule*
- *GDP – ground delay problem*
- *GHP – ground holding problem*
- *ATFM – air traffic management*
- *ETA – estimated time of arrival*
- *ETD – estimated time of departure*
- *PAX – passengers*
- *IMC – instrumental meteorological conditions*
- *VMC – visual meteorological conditions*

I. INTRODUCTION

The Philadelphia airport (ICAO. KPHL) is an international airport located in Pennsylvania State and the most important airport in the Delaware Valley. This report analyses the suitability of multiple ATFM programs on the airport.

II. REGULATION GENERAL PARAMETERS

In order to be able to analyse the airport arrival demand, a gathering data process was needed by taking all the flights for an operations day. Fig. 1 shows all the flights per hour after processing them:

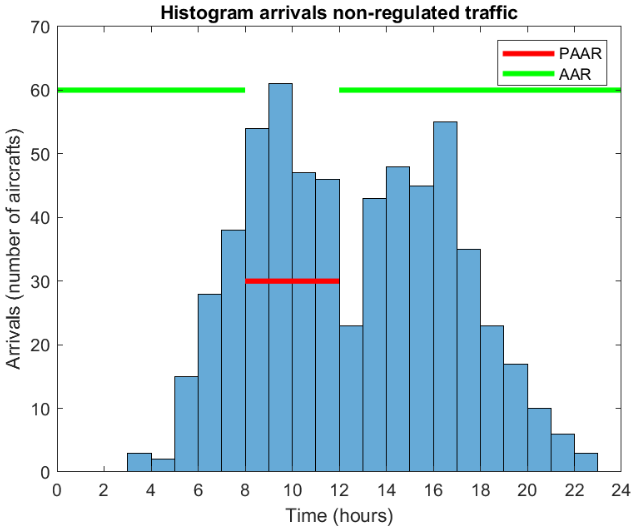

Figure 1: histogram non-regulated arrival demand

A. Capacity definition

FAA provides data and models from which nominal and reduced capacity of the airport (AAR, PAAR) can be defined. Nominal capacity corresponds to the VMC capacity while reduced capacity corresponds to IMC capacity (see Fig. 2 and 3).

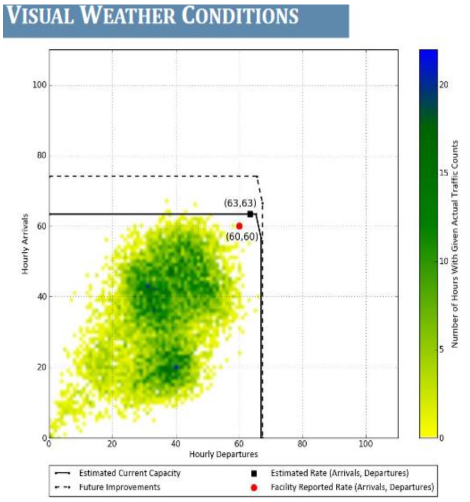

Figure 2: airport capacity profile for VMC [1]

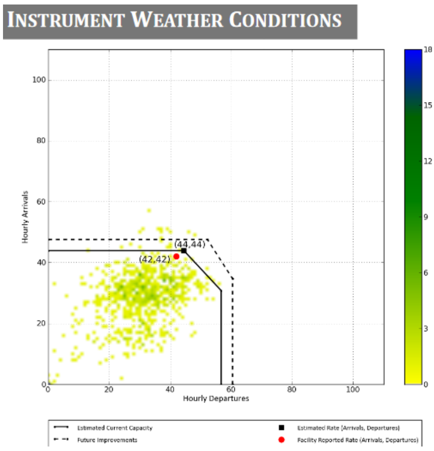

Figure 3: airport capacity profile for IMC [1]

From the previous graphs, it can be deduced that the AAR is 63 and the PAAR is 44, however for simplification purposes the following AAR has been set to 60 flights/hour and PAAR to 30 flights/hour:

- AAR = 60 → slots of 1 minute
- PAAR = 30 → slots of 2 minutes

B. Regulation relevant times and total delay

Once all this data has been achieved, it is possible to decide when to impose a regulation, from Fig. 1, it can be appreciated that the highest demand peak is from 9:00 AM to 10:00 AM, therefore a threshold of one hour has been considered in order to deal with possible contingencies which makes the start regulation time (Hstart) at 8:00 AM.

Finally, the file hour for the regulation (Hfile) should be at 5 AM, however during testing of the simulations quickly is noticed that no air delay is produced and for the sake of academic purposes, it is not worth it. Therefore, Hfile has been moved to 6:00 AM in order to produce air delay.

Regarding to the end of the reduced capacity (Hend) as instructed in the statement of work it has to last four hours, therefore Hend is at 12:00 PM.

With all this data, it is possible to plot the aggregated demand function and the nominal and reduced capacity constraints.

From Fig. 4, the HNoReg, the time where the delay is recovered (nominal capacity merge with aggregated demand) is at 17:04 PM.

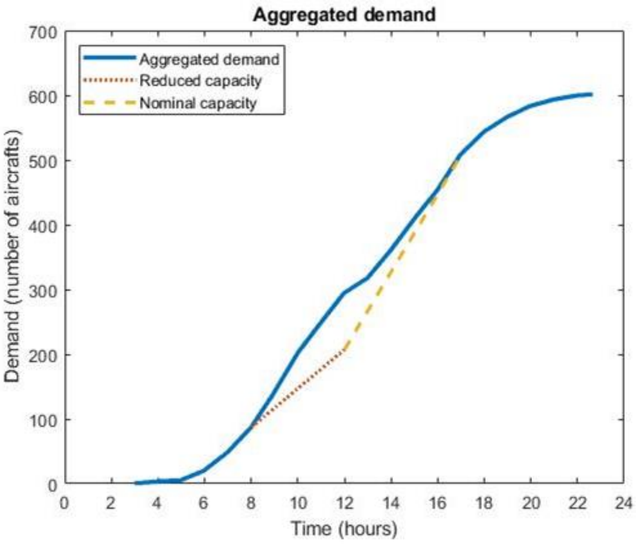

Figure 4: aggregated demand plot

The enclosed area corresponds to the total delay, integrating; the total delay obtained is 21387 minutes.

- Hfile = 6:00 AM
- Hstart = 8:00 AM
- Hend = 12:00 PM
- HNoReg = 17:04 PM

III. RBS REGULATION

RBS is the simplest regulation studied. It is based on first-in first served idea, which means that flights are assigned by ETA order.

In order to apply the regulation, arrivals must be classified in two different types of flights:

- Non-affected: flights not included in the regulation. Those whose ETA is before Hstart or after HNoReg.
- Controlled: flights within the regulation.

Those flights already flying when the regulation is defined (ETD < Hfile) will have to apply airborne holding, while the others (ETD > Hfile) will have to apply ground holding.

A. Results

	Total Delay (min)	**Max Delay (min)**	**Average Delay (min)**	**Standard Deviation (min)**
Total Delay	21447	114	50,464	37,258
Air Delay	327	82	32,7	28,987
Ground Delay	21120	114	50,892	37,358

Table 1: RBS results

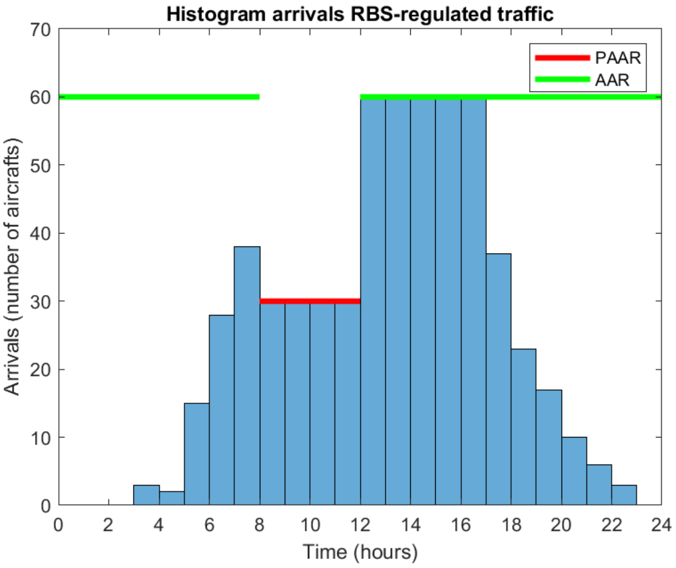

Figure 5: histogram RBS-regulated arrival traffic

As seen in Fig. 5, the regulation restricts the number of arrivals to PAAR during the reduced capacity time, and it maximises the use of AAR after Hend to recover the delay generated.

B. *File time effect on RBS*

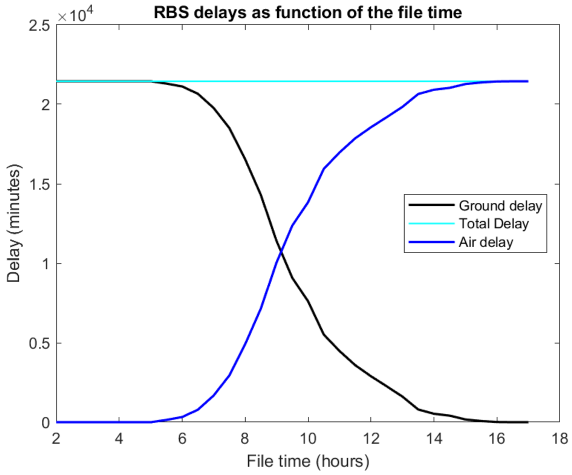

Figure 6: RBS delay as function of Hfile

As seen in Fig. 6, as file time increases more flights are already flying (ETD < Hfile), therefore, more flights will have to apply airborne holding, which means more air delay and less ground delay.

IV. GDP REGULATION

The main objective of GDP regulation is to manage the capacity and demand of the airport, holding aircrafts on ground and assigning slots considering flight ETA's. One of the main objectives is to reduce the airborne holding, therefore, GDP regulation will reduce burned fuel and CO_2 emissions comparing with RBS.

In order to apply the regulation, arrivals must be classified in three different types of flights:

- Non-affected: flights not included in the regulation.
- Controlled: flights within the regulation.
- Exempt: flights within the regulation although they are given priority. Those flights are assigned by the following criteria:
  - International flights (except those departing from Canada).
  - Flights departing from an airport further than the GDP radius.
  - Flights already flying when GDP is defined (ETD > Hfile).

The selection of the exempt flights will strongly depend on two factors:

- Program radius, which will determine the dimension of the program, and the number of flights affected.
- File time

The program could also be implemented using scopes instead of a defined radius.

A. *Results*

Using a 700 NM radius (see Section C):

	Total Delay (min)	**Maximum Delay (min)**	**Average Delay (min)**	**Standard Deviation (min)**
Total Delay	21447	349	50,464	37,258
Air Delay	225	56	22,5	19,823
Ground Delay	21222	349	51,137	73,287

Table 2: GDP results

As seen in Table 2, air delay is reduced if compared to RBS while maximum delay increases. The standard deviation also increases, which means that delays assigned to the flights differ much more from the average delay than they did in RBS.

B. *Radius and file time effect on GDP*

The regulation radius will strongly affect the results, as seen in Fig. 7. When radius increases, the number of controlled flights increases and exempt flights decreases (see Fig. 8), therefore, ground delay assigned will increase and air delay will decrease.

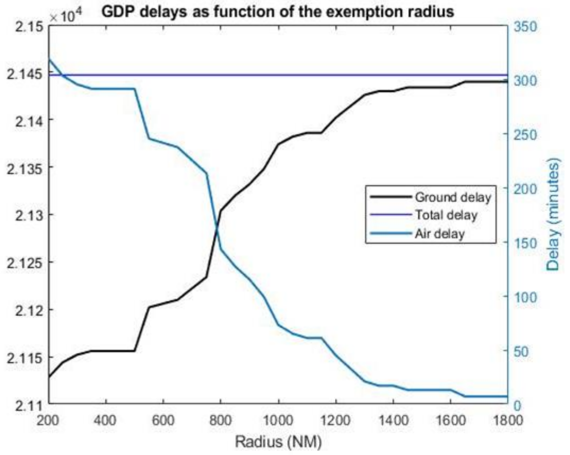

Figure 7: GDP delay as function of the radius

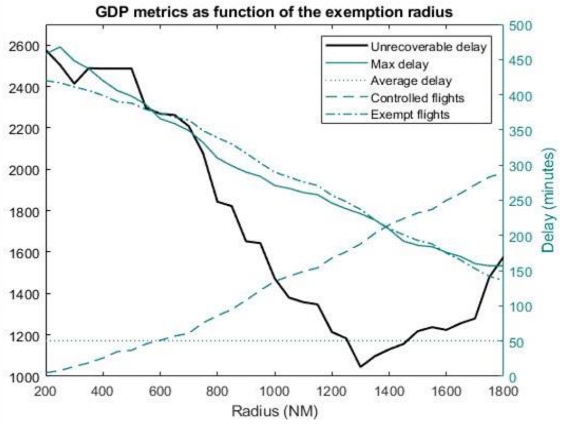

Figure 8: GDP metrics as function of the radius

The regulation behaviour for file time increases will be the opposite (see Fig. 9): as file time increases more flights are already flying (ETD < Hfile), therefore, the number of controlled flights will decrease (see Fig. 10) and the exempt flights will increase, which means more air delay and less ground delay.

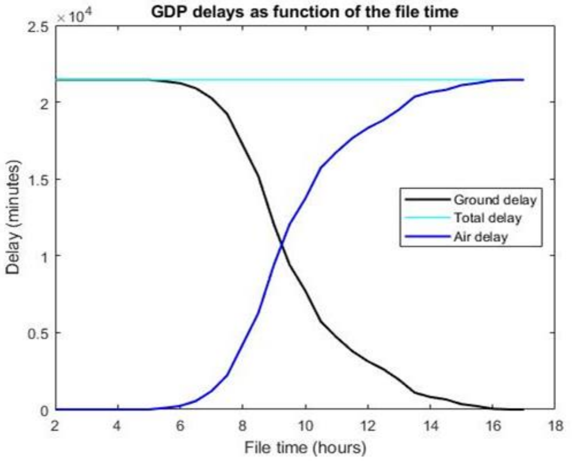

Figure 9: GDP delay as function of Hfile

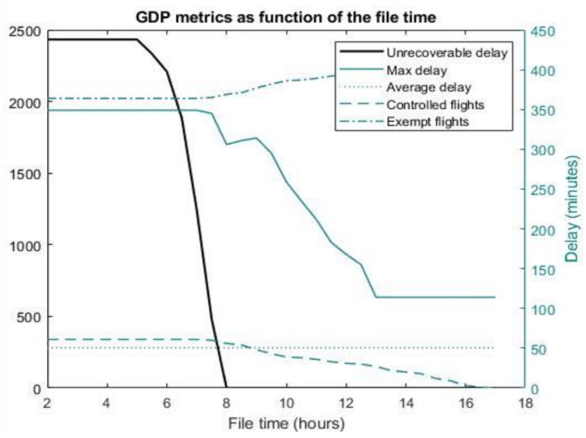

Figure 10: GDP metrics as function of Hfile

C. *Other metrics and optimal radius*

Results from Fig. 8 and 10 shows the unrecoverable delay values for different radius and Hfile. The unrecoverable delay has been computed as the delay that will be realized even if the delay is cancelled at Hstart, and assuming the ideal situation that all flights in ground holding departure at Hstart.

As seen in Fig. 8, as radius increases unrecoverable delay decreases until 1300 NM, where the tendency is reversed. From the data an optimal value for radius can be selected, which will vary from 700 NM to 1300 NM. Considering that for values over 700 NM the amount of air delay is very low and, which could lead to a saturation of the airport ground capacity, 700 NM would be an optimal value for GDP radius.

From Fig. 10, the data shows that from 6:00 AM to 8:00 AM the unrecoverable delay goes from maximum value to zero, as already explained, the ideal situation of all flights departing at Hstart when GDP is cancelled, generating a non-existent unrecoverable delay situation as of 8:00 AM (Hstart).

As Hfile has been defined at 6:00 AM (see Section II) when unrecoverable delay still has maximum values, around 2500 minutes, it would be a good option to delay Hfile for 30 minutes or 1 hour (only for GDP). Even so, as the defined Hfile is a common value for all the studied regulations, 6:00 AM is a good value because delaying Hfile has other inconveniences as increasing airborne holding and as consequence, increasing CO_2 emissions.

V. GHP REGULATION

The objective of GHP regulation is to delay flights departures to avoid overloading the system using ground holdings. In order to optimize the slot assignations, the method used is the minimization of the flight costs, which considers different factors as PAX, fuel cost….

A. *Flight cost function*

The objective of the regulation is to minimise the following equation:

$$min \sum_{f} \sum_{t} C_{ft} X_{ft} \ where \ C_{ft} = r_f(t - e(f))^{(1+\varepsilon)}$$

- C_{ft}: cost associated to flight *f* at slot *t*
- X_{ft}: binary variable, takes value 1 if flight *f* assigned to slot *t* and 0 otherwise.

Cost function C_{ft} depends on 4 variables:

- t → slot time
- $e(f)$ → flight *f* ETA
- ε → delay cost factor
- r_f → cost coefficient

Cost coefficient r_f depends on different parameters:

- Fuel: fuel cost depends on flight type (international or regional) and delay type (air delay or ground delay). For more information see Section VI.
- PAX: all passengers have a delay cost based on delay duration, the care cost [2].

Delay duration (hours)	Cost (USD / min)
0 – 2	0.02
2 – 3	0.05
3 – 5	0.08
Over 5	0.13

Table 3. Delay cost [2]

- Connecting PAX: those passengers with connecting flights will have an extra cost, the reaccommodation cost [2]. The reaccommodation cost is modelled by the following equation:
-

$$C_R = k \cdot \ln {t_D}^2$$

- t_D→ delay duration
- k → constant value. It is computed knowing that contribution of the care cost to the total is 20%. Therefore, each time slot in Table 3 will have a different value for *k*.

- Compensations: each PAX can claim an economic compensation for delays over two hours, which is proportional to flight length [3].

Flight length (Km)	Compensation (USD)
0 – 1500	250
1500 – 3500	400
+ 3500	600

Table 4. Compensation costs [3]

- Other costs: includes crew (24.55 USD/min) and maintenance costs (12.01 USD/min) [4].

B. *Problem constraints*

In order to solve the optimisation problem, two constraints have been imposed (one for each flight and one for each slot):

1. All flights must be located once:

$$x_{i1} + x_{i2} \ldots = 1$$

2. Slots cannot be assigned more than once:

$$x_{1j} + x_{2j} \ldots \leq 1$$

Xij is a binary constraint which takes value 1 if flight *i* is assigned to slot *j*, and 0 otherwise.

C. *Results*

	Total Delay (min)	Maximum Delay (min)	Average Delay (min)	Standard Deviation (min)
Total Delay	21447	159	50,464	38,047
Air Delay	41	10	4,1	35,103
Ground Delay	21406	159	51,581	37,804

Table 5: GHP results

D. *GHP cost vs RBS and GDP*

Applying the same criteria for cost function for all three types of regulations, the evolution of the cost as ε increases is ploted in Fig. 11.

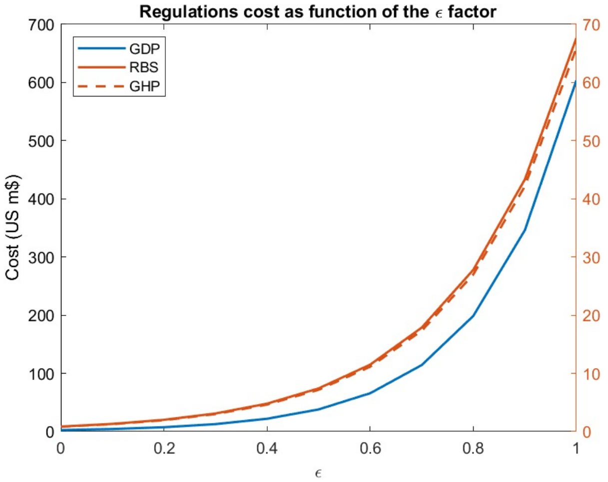

Figure 11: regulation costs as function of ε

Fig. 11 shows how RBS and GHP costs are very similar even though RBS is slightly higher because the total air delay is greater, which means higher fuel cost (see section VI).

On the other hand, GDP cost is notoriously higher. The reason is that, as seen in subsection A, the total cost strongly depends on delay duration and, as Fig. 12 and 13 shows, GDP delays for some flights last much longer than in RBS and GHP which produces an exponential raise in regulation cost.

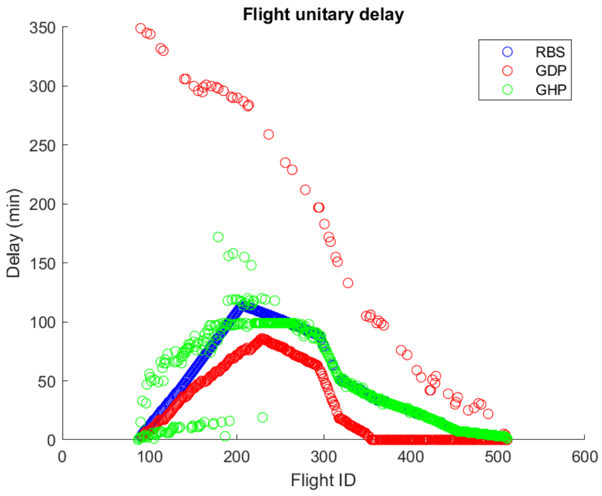

Figure 12: flight unitary delay for RBS, GDP & GHP

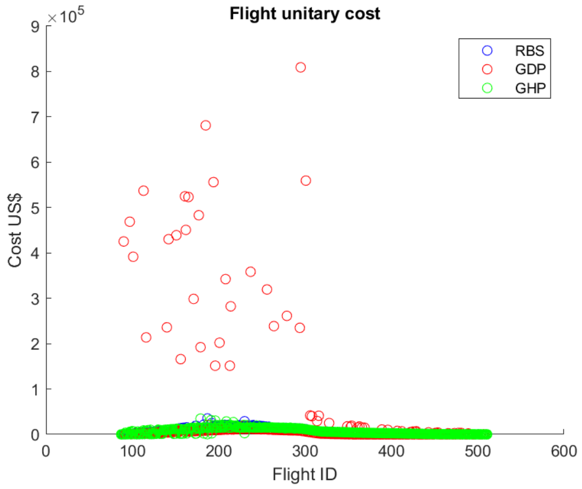

Figure 13: flight unitary cost for RBS, GDP & GHP

E. *Optimal ε*

Regarding the ε parameter, it relates the delay with the delay cost. Basically, it is a penalizing factor. For ε=0 the slope of the cost plot is flat whereas ε=1 the slope increases to almost a vertical line (see Fig. 11).

The normal values for epsilon are between 0.2 and 0.5, values equal or higher to 0.5 represents big disruptions in an airline operation, which can produce a domino effect during days or months (for instance operations collapse from Vueling in Barcelona during 2016's summer), a terrorist attack (for instance 9/11), a plane crash or a grounding for the fleet (for instance Boeing's 737 MAX grounding).

On the other hand, values lower than 0.2 means that the impacts from the delay are low, therefore, they are unrealistic.

Finally, the optimal value has been computed by comparing a range of values inside the valid scope for which in this case it is ε=0.3.

Fig. 14 shows the total costs for optimal ε, as already stated in section D, RBS and GHP have similar costs while GDP cost is much higher.

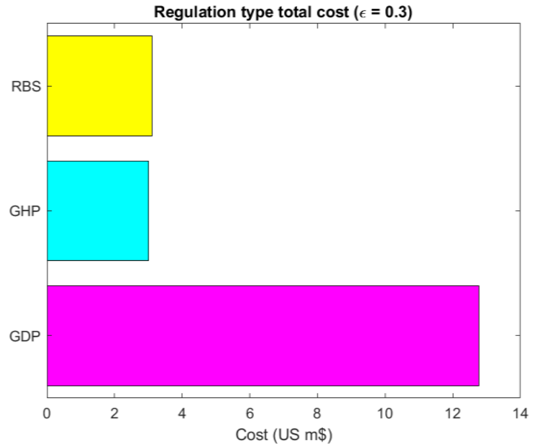

Figure 14: regulation costs for optimal ε

VI. SUSTAINABILITY AND FUEL COST FOR RBS, GDP & GHP

This section analyses the environmental impact of the analysed regulations: RBS, GDP and GHP. This is done by computing the amount of fuel burned during delays generated by the regulations, and the cost and amount of CO_2 emissions associated.

A. *Data selection*

In order to compute the fuel burned and CO_2 emissions during the regulation operation in Philadelphia two aircrafts have been taken into account: B737-800NG and A330-300 in order to work with regional and international flights.

The reason to choose these two aircraft are based in that both are twin jets, have a big sitting capacity in their category and have an intermedium fuel burn in comparison to modern jets like the A220, A320 NEO or the B787. On the other hand, there would be the older and less efficient jets like the MD88, B717 and early versions from the B737 family. In addition, these are two models of aircrafts widely used by American Airlines, which is the main operator in PHL airport [6].

It is important to mention that trijets and quad jets have not been taken into consideration because of the lack of relevance in numbers and the tendency of the aeronautical market to more efficient and smaller twin jets.

	B373-800NG	**A330CEO**
Air Fuel Consumption	40 Kg/min	95 Kg/min
Ground Fuel Consumption	1.8 Kg/min	3.5 Kg/min

Table 6: fuel consumptions [7]

For academic purposes it has been considered that the auxiliar power unit (APU) is running during the 100% of ground delay time. However, it is important to state that a quick look to PHL taxi charts (see Fig. 15) shows that 95% of all the stands are not remote and have all the ground services available whereas the 5% lacking represents the cargo aprons for the different freighter operators based in the airfield.

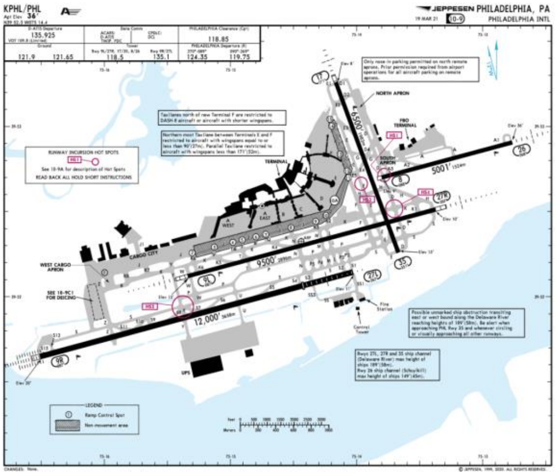

Figure 15: PHL chart [1]

Therefore, it could also be considered that external power and pneumatic supply is provided making the environment eco-friendlier and cheaper. However, this limits the scope of the research to specific cases and therefore less useful.

Other important data:

- Average fuel price: **0,6 USD/kg** [5]
- CO_2 produced per kg of fuel burned: **3,16 kg** [8]

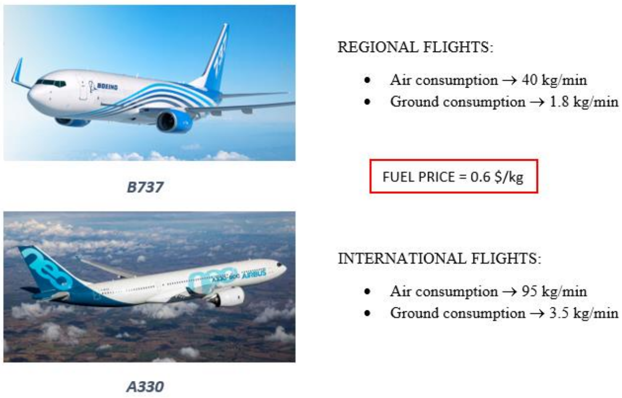

Figure 16: fuel data summary

B. Results

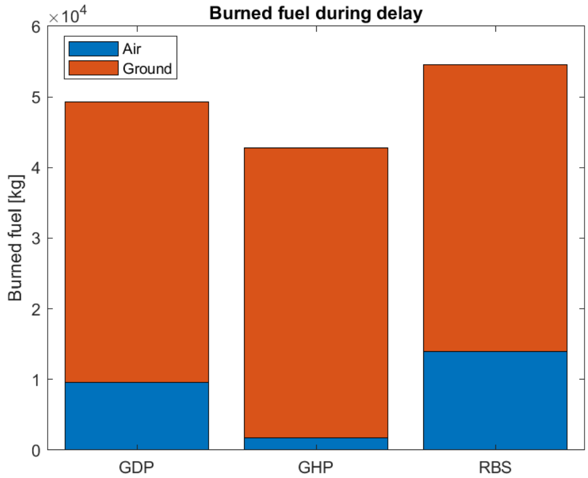

Figure 17: fuel burned during delay

As seen in Fig. 17, the amount of fuel burned is larger for regulations with more air delay, therefore, as fuel cost and CO_2 emissions will be directly related to the amount of air delay generated (see Fig. 18 and 19).

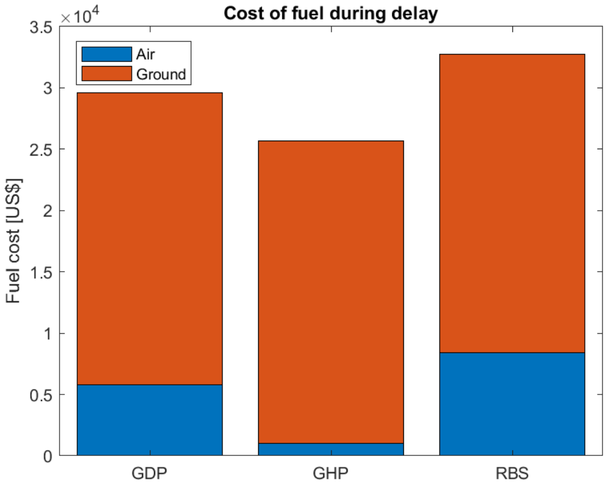

Figure 18: fuel cost

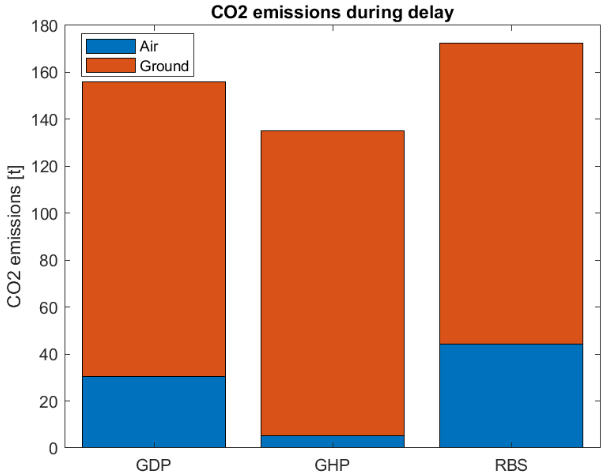

Figure 19: CO_2 emissions

From the previous graphs the GHP is the most fuel-efficient regulation since it is the regulation with less air delay. However, it is important to recall that fuel is not the only decisive factor when choosing a regulation as other factors play important roles in delay costs (see Section V. A).

VII. AIRPORT CAPACITY STUDY

The objective of this section is to study the capacity of the airport optimising the balance between arrivals and departures during the regulation time.

In order to do that the regulation time has been divided by 15 minutes slots, which means that for the 4 hours regulation, from Hstart to Hend, the demand has to be distributed between 16 slots. The method to find the slots capacity is simple, data from FAA charts for IMC (see Fig. 3) which shows the capacity per hour is taken and translated to data for 15 minutes slots. e.g.: the maximum capacity is (44,44) which is translated as a maximum capacity of (11,11) for 15 minutes.

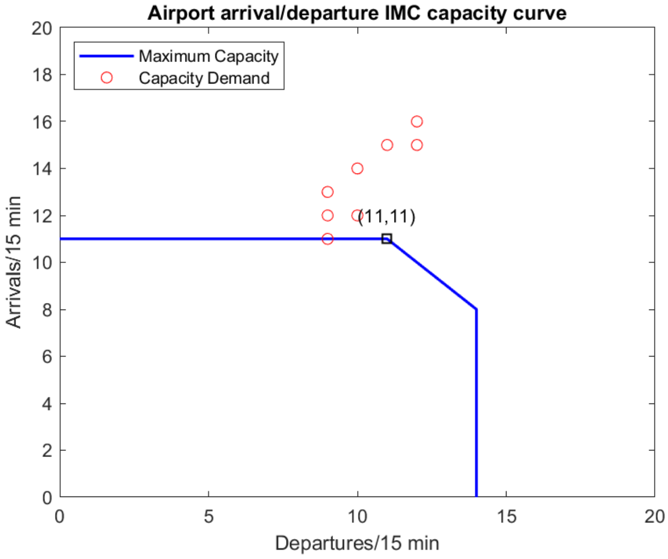

Figure 20: IMC capacity curve

As seen in Fig. 20, the demand is clearly over capacity. To find the optimum relation between arrivals and demands, the following equation used to compute the slot utilization must be maximised:

$$max_{u,v} \sum_{i=1}^{N} (N-i+1)(\alpha u_i + (1-\alpha) v_i)$$

- u_i: number of arrivals at slot i
- v_i: number of departures at slot i
- N: number of slots
- α: weight coefficient. This parameter will determine if arrivals (α→1) or departures (α→1) are maximised.

Figures above show how α determines the capacity:

- Fig. 21: α=0, only departures are maximised.

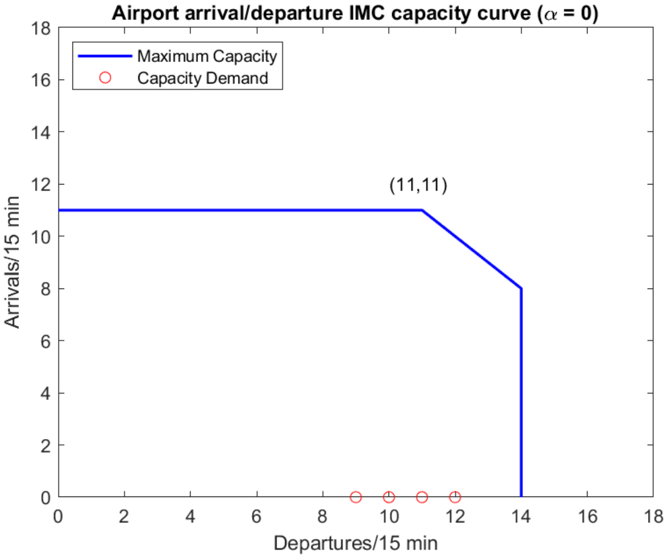

Figure 21: IMC capacity curve for α=0

- Fig. 22: α=1, only arrivals are maximised.

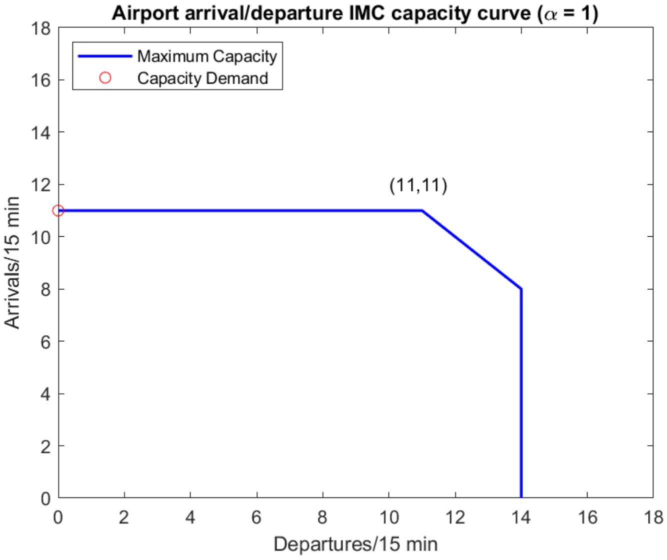

Figure 22: IMC capacity curve for α=1

- Fig. 23: α=0.7, since α is closer to 1, arrivals are prioritised.

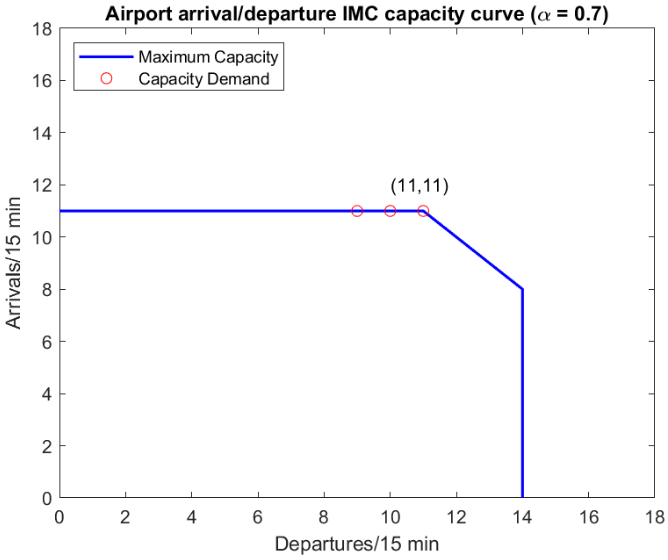

Figure 23: IMC capacity curve for α=0.7

A. Problem constraints

In order to solve the optimisation problem, five constraints have been imposed, three to define the capacity and two to define the demand:

1. Capacity:

$$u_i \leq 11$$
$$v_i \leq 14$$
$$u_i + v_i \leq 22$$

All three constraints are taken from the FAA information and define the maximum capacity represented with a blue line in Fig. 20. First and second constraints define the maximum number of arrivals and departures, and the third one defines the maximum number of operations for 15 minutes.

2. Demand:

$$u_i \leq \#\, arrivals_i$$
$$v_i \leq \#\, departures_i$$

Both constraints set the demand of arrivals (first) and departures (second) for slot *i*, which are taken from the airport data.

B. Capacity and demand

Fig. 24 and 25 show the accumulated demand of arrivals and departures during the regulation time.

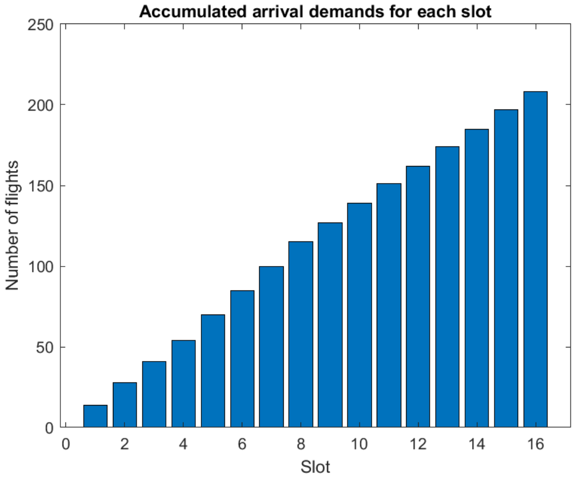

Figure 24: arrivals accumulated demand

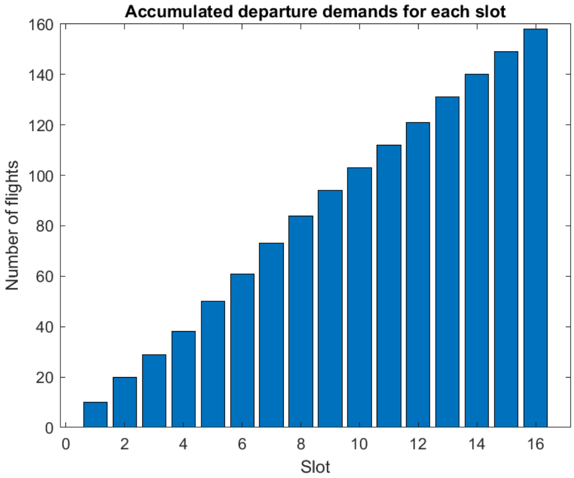

Figure 25: departures accumulated demand

Arrival demand (208) is greater than departure demand (158). Computing the average demand per slot the result is 13 arrival demands per slot and 10 departure demands, which means that, since the maximum capacity is (11,11), the arrival demand is over capacity while departure demand is under capacity.

In order to balance the demand, arrivals should be prioritised, which is translated as having an α parameter over 0.5. By doing this, the queues formed by those flights which cannot be allocated in the slot are minimised.

C. Optimal α and extra slots

As already exposed, the optimal α will be a value that maximises the slot utilization or, in other words, minimise the number of flights in queues.

Fig. 26 shows the evolution of queues for all possible α values. For values of α between 0.1 and 0.5 there are no queues for departure demands and, for values between 0.6 and 0.9 the queues for arriving flights decrease and those for departing flights increase, but the total number of queues is constant for α values between 0.1 and 0.9. Therefore, the optimal value of α goes from 0.6 to 0.9.

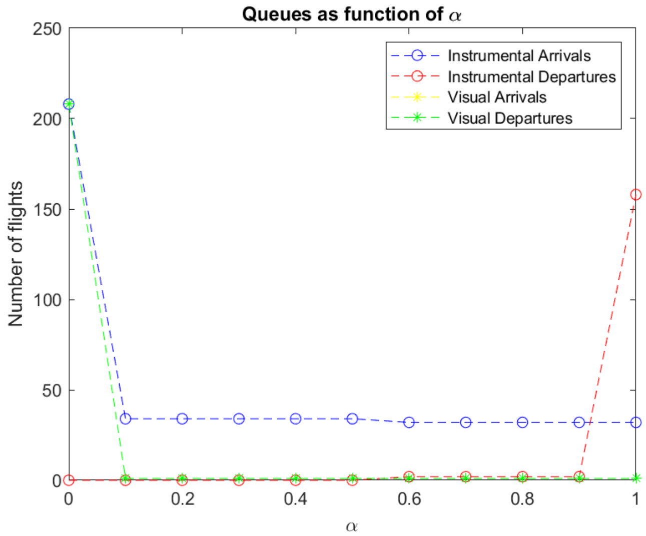

Figure 26: queues as function of α

The selected value for optimal α is 0.7. As seen in Fig. 27, flights in queue for IMC arrivals is 32 and for departures is 2. Since the maximum number of arrivals in a slot is 11, three extra slots will be required to deal with the generated queues, which has an impact of 45 extra minutes.

Fig. 23 shows that, for α=0.7, arrivals are prioritised over departures, even then, departures have also great capacity since α value is reasonably near 0.5, which allows the airport to keep allowing departure operations while arrival queue is absorbed, generating a minimum impact.

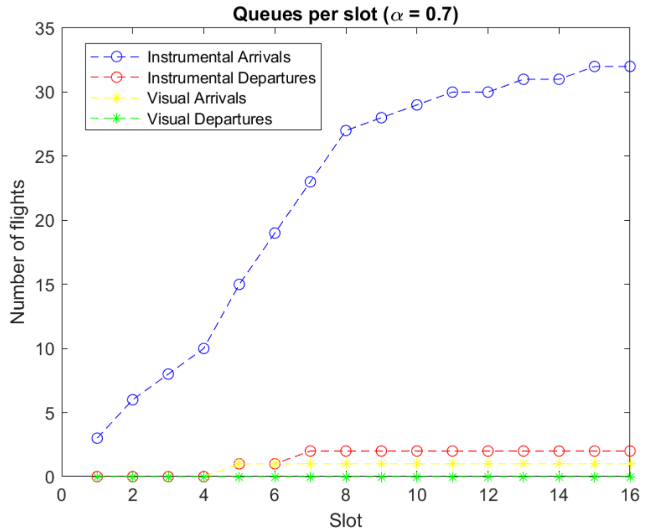

Figure 27: queues for optimal α

VIII. CONCLUSIONS

Regulations implemented on an airport severely impacts the airport and airlines performance. There are three main aspects to consider when choosing an optimal regulation: environmental impact, economic impact and airport capacity impact.

- RBS: is the one that generates more air delay, which means that has the higher environmental impact. Even so, the amount of delay generated per flight is the lowest one which means that the extra fuel cost produced by air delay is compensated with a lower probability of cancelling flights and less care costs.

- GDP: it generates less air delay than RBS, which means that the environmental impact is lower. However, having exempt flights which have priority generates an amount of delay for some flights too high, sometimes tripling the delay generated by RBS or GHP, which means that a great number of cancellations, reallocations… must be applied, making costs and airlines workload grow exponentially, dismissing GDP as a feasible option for PHL airport.

- GHP: it is the one with less air delay, reducing the environmental impact, but also increasing the probability of the airport ground space saturation. It is the cheapest one to implement since the objective of the regulation is to minimise costs.

It is for those reasons that the best ATFM regulation to implement in PHL airport is GHP, since it has a low impact in flights delay duration and minimises costs. Although it must be applied in an efficient way, balancing air, and ground delay, in order to avoid an airport saturation due to having an amount of ground delay impossible to absorb.

Moreover, if the demand is low RBS is more recommendable since it has a lower impact in airport functioning.

Regarding the Airport Capacity study (section VII), it is wider than the studied regulations since it does not only work with arrivals but also departures.

It is clearly stated that with an optimal α value a regulated airspace has a noticeable impact on the airport capacity, but it can be handled without generating great delays. In other words, a good balance between arrivals and departures prioritisation considering the number of demands of each type is crucial to avoid large queues and delays.

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