Adopt an Airport: Adolfo Suárez Madrid-Barajas Airport (MAD)

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Abstract

Presently, air traffic flow management is an essential and heavily researched domain within the aeronautical industry. Through the progressive development and implementation of various strategies, not only have substantial cost savings been realized, but an important amelioration regarding aircraft emissions has been produced. This study employs a quantitative approach via real-world arrival data simulation provided by FlightRadar, at Adolfo Suárez Madrid-Barajas Airport, of two distinct ATFM methodologies in order to reduce cost and delay, for the means of comparison and the study of relevant metrics; by the definition and use of Key Performance Areas and Key Performance Indicators. These methodologies are both realized via a custom Matlab code, they comprise themselves of a Ground Delay Program (GDP) and a Ground Holding Program (GHP). While GDP employs a First-Come-First-Serve algorithm (minimizing air delay) for sequencing, the GHP makes use of linear integer programming to reduce the cost for the allocation of the flights in their corresponding slots. Furthermore, a intermodality study has been made, substituting some flights by rail and comparing the cost obtained with such cancellations. Eventually, the results reached confirm the nonexistence of an ideal program, showing the advantages and problems that arise in both cases; and emphasises the necessity to determine and stipulate constraints and preferences before the implementation of either strategy. Future work aims at the creation and use of different algorithms (such as genetic algorithms)and the refinement of the delay cost function through more advanced modelling techniques.

Keywords: ATFM, GDP, GHP

1. Introduction

Currently, air traffic flow management is an essential and heavily researched subject within the aeronautical industry. A substantial amount of delay, costs and environmentally negative events have been reduced due to the implementation and progressive development of these techniques. In this work it is presented two different methodologies applied to arrivals in Adolfo Suárez Madrid-Barajas Airport during a period of several hours with a capacity much lower than the nominal airport capacity. These two methodologies are Ground Delay Program (GDP) and Ground Holding Program (GHP) (both implemented in Matlab via custom code).

This project revolves around a simulated scenario wherein an important decrease in airport arrival capacity takes place during several hours. The magnitude of this decrease is such that it obliges a regulation to be enforced in order to ensure operational safety at the aerodrome. Both methodologies stated earlier are applied during this time-frame to evaluate the data regarding cost and delay. It is worth noting that in real-world situation, adverse weather phenomena, runway conditions, poor visibility or any other abnormal activity may impede the nominal functionality of the airport.

Moreover, the project aims to compare and analyze these two different approaches, focusing on the relevant metrics. These not only encompass data such as total cost and delay, average cost and delay per flight, cost and delay standard deviation and relative standard deviation, but also the effect each parameter and perturbation produces at a large scale in them.

1.1. Airport Capacities and Arrival Data

The airport nominal capacity is approximated to 60 flights per hour (1 flight every minute) (EUROCONTROL, 2020). When setting a reduced capacity, a semi-arbitrary value is chosen; that is because enough delay must be produced in order to not render the study useless. Not only for the sake of simplicity concerning slot time intervals but for the correct magnitude of total delay, 20 arrivals per hour (1 every 3 minutes) has been selected.

The arrival data used for the whole simulation has been obtained via FlightRadar and concerns the 13$^{\text{th}}$ of September 2023, a day where 592 flights where scheduled to land at Madrid Airport.

1.2. Regulation Definition

When there is an important capacity reduction during a large interval of time the situation must be studied and, if the demand exceeds the capacity a regulation must be applied. For this work, the reduced capacity will be set from 10.00 to 15.00. The demand profile shown in Figure 1 allows the visualization of the surpassing of reduced capacity (shown in red) that would be predicted to occur if no regulation were to be set in place. Note this problem would not have arisen were it not for this regulation, as in no moment does demand exceed the nominal airport capacity (shown in green).

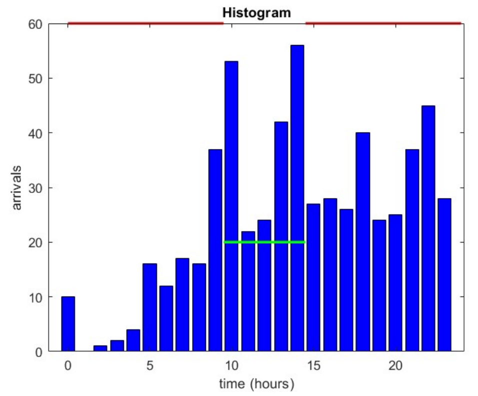

Figure 1: Histogram of the demand with no regulation

The regulation applied has consisted in the assignation of every arriving flight within the regulated time-frame to a slot. Each slot can be assigned to a maximum of 1 aircraft (as 2 cannot land at the same time) and it's length is: 3 minutes for the reduced slot and 1 minute for the nominal one. The latter times are associated to airport capacity, as has previously been defined in Subsection 1.1. As a consequence of the latter assignation, aircraft will be forced to arrive later than their estimated time of arrival (ETA). Note that none will arrive before-hand.

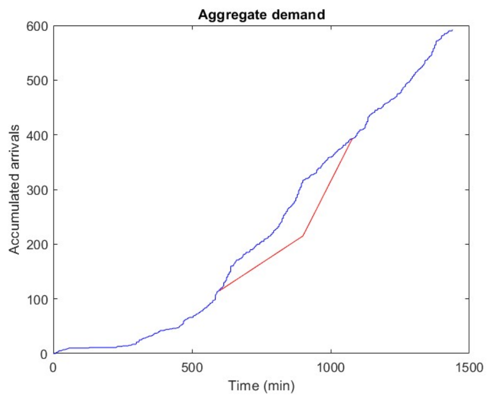

Figure 2: Aggregate demand during the day

The application of the regulation results in the demand plot shown in Figure 2. In the latter, the blue line represents the aggregated demand during the day *e.g.* at the end the total aggregated demand is 592 flights (*i.e.* the total number of flights in the day). The red line with the lower slope represents the reduced capacity that occurs due to the regulation enforced from 10.00 a.m to 15.00 a.m, where the last reduced capacity slot is set (3 minutes). The following, higher-sloped line shows the way in which the capacity is recovered once the reduction halts. Therefore, when the latter reaches the aggregated demand (17:58), the regulation is no longer perceived in the system and can be considered to end.

Furthermore, this graph also provides the total delay, which will be constant along all the methodologies applied. This is because the delay depends only on the regulation. The delay is computed by finding the area between the capacity lines (red ones) and the demand line (blue one) of Figure 2. In this case, the total delay is approximately 360 hours (to be accurate, 21609 minutes). Later on this project the total delay is calculated again and differs a little from this value. This is because of the calculation method.

Once it has been computed the time where the regulation ends, a new histogram can be plotted. Now there is not a single moment where the demand exceeds the capacity, as can be seen in Figure 3:

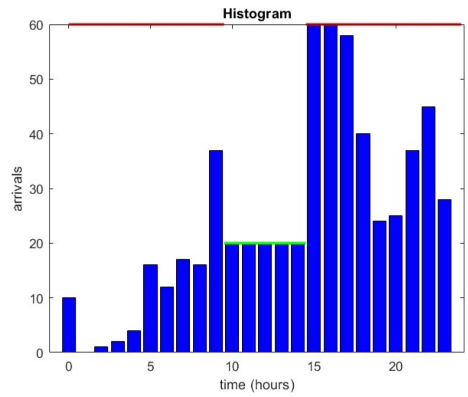

Figure 3: Histogram of the demand with the regulation applied

Knowing the value of the total delay, both algorithms (GDP and GHP) are applied. Firstly, the GDP will be taken into account.

2. Ground Delay Program

2.1. Methodology

The Ground Delay Program relies firstly on the categorisation of the incoming flights (determining their exemption dependant on various parameters) to the proceed with the First-Come-First-Serve philosophy slot allocation algorithm. The aim of this approach is to minimize the airborne delay. Besides, the program also incorporates mechanisms to handle the cancellation of a flight that is anticipated to experience a delay surpassing a certain threshold, and compressing the latter aircraft in order to fill all slots and reduce the time at which the regulation is no longer experienced by the system.

The algorithm classifies the flights into two types: Exempt Flights and Controlled Flights. The criteria that is used to classify is based on a radius of exemption (expressed in kilometers), the origin airport and the scheduled time of departure.

To complete the last classifying criteria shown above, one must define a file time that is the time when the regulation is announced. If the flight is already flying at that instant or 30 minutes later (in order to avoid applying ground holding to a flight ready to departure) that flight is exempt of the regulation. In other words, if the flight estimated time of departure (ETD) is before file time plus 30 min, the flight is classified as exempt. In this work, the file time is defined at 8:20, therefore arrivals with a lower ETD than 8:50, coming from further than a distance of 2000 km or with their origin airport lying outside the European Civil Aviation Conference (ECAC) are considered exempt.

When applying the algorithm to the list of flights arriving to the airport, the total number of flights affected by the regulation is 278. Specifically, the number of controlled and exempt flights are 182 and 96, respectively. In this work, the delay applied to all controlled flights will be ground delay and the delay applied to all exempt flights will be airborne delay. Note that ground delay is much better for the environment because there is not unnecessary fuel burning. Besides, it is cheaper to maintain the flights on the ground rather than maintain them flying.

Once the flights are classified, the algorithm gives priority to those exempt flights and assigns them a slot (following First-Come-First-Serve), applying air delay when needed. By doing this, the GDP minimizes the air delay, given that all the slots are empty at the moment of the assignation and, consequently, it is very likely that the exempt flights get assigned to a slot very close to their ETA. Upon finishing slot assignation for exempt flights, the same process is repeated for controlled flights, taking into account that a significant number of slots will already be occupied by exempt flights. This flights will receive much larger delays, but in the form of ground delay.

2.2. Cancellation at Starting Time

Furthermore, the project also contemplates the scenario in which the regulation is cancelled just at its starting time. In this case, there would be some aircraft that would have already been delayed at said starting time. This delay is called unrecoverable delay, as it has already been done and can't be recovered. In order to compute it, it must first be defined a new variable, the CTD (Controlled time of Departure), which is the result off adding the delay obtained in the GDP algorithm to the original ETD of each flight. There are now have 3 cases to study with regard to the unrecoverable delay:

1. $ETD > Hstart$: No unrecoverable delay
2. $CTD < Hstart$: $Unrecoverable\ delay = CTD - ETD$. (All the delay has already been done at the start of the regulation).
3. $ETD < Hstart < ETD$: $Unrecoverable\ delay = Hstart - ETD$. (When the regulation is cancelled, only part of the delay has been done).

2.3. File time and Radius selection

The value of the Unrecoverable delay depends on the file time and radius, as do ground and air delay. These variables were initially decided arbitrarily, consequently, they may not yield the optimal balance between these 3 Key Performance Indicators. In order to obtain these optimal values, ground, air and unrecoverable delays are calculated with a range of values for file time and radius. The results are the following:

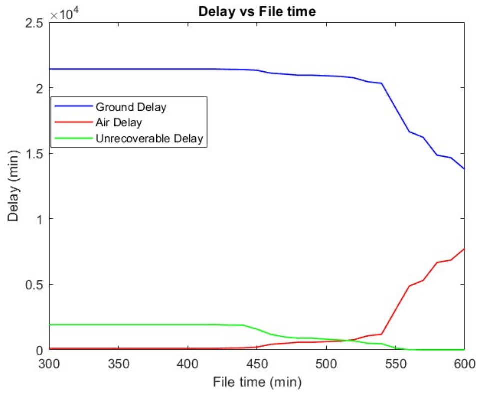

Figure 4: Ground, Air an Unrecoverable Delay as a function of the file time

In Figure 4, a gradual decrease in unrecoverable delay is observed, starting at 2000 min a file time of around 450 min (7:30) until 0 at 550 min (9:10). In the same interval of time, an increase of the same magnitude is observed for the air delay. After 9:10, a sharp increase in air delay takes place, (with the consequent decrease of ground delay, as the sum of these to parameters is constant) until 10:00, the starting time of the regulation. Finally, from this graph we can deduce an optimal file time at approximately 500 min (8:20), since at this time air delay is quite low, which is the objective of the GDP, and unrecoverable delay is reduced by half, giving us more flexibility in the event of cancelling the regulation. Note that this value coincides with the one originally selected.

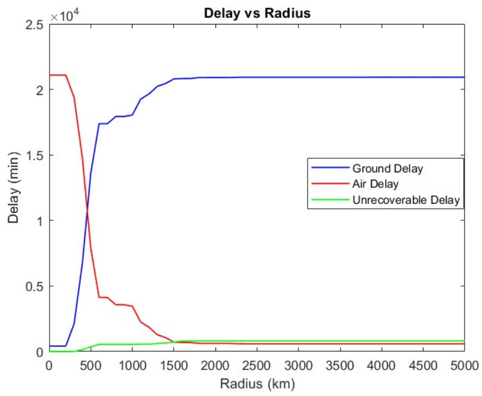

Figure 5: Ground, Air an Unrecoverable Delay as a function of the radius of exemption

In Figure 5, a sharp decrease in air delay is observed from 0 to 1500km, where it stabilizes. Unrecoverable delay starts increasing at around 500km until it also stabilizes at 1500km, and intersects at that point with air delay with a value of approximately 800min. Therefore, the optimal value for the radius sits within the range of 1500-2500km, as air delay is minimized. Although selecting a value under 1500km would reduce unrecoverable delay, the increase in air delay would be much more significant, which would not be optimal from a GDP standpoint. Finally, selecting a value from 2500km onward, in spite of not altering values significantly, would not be realistic, given that most of Europe would already be inside the radius. Again, the value initially selected for the radius is inside this range.

2.4. Airline Cancellation

One final scenario considered in the GDP, is that of the main airline in the studied airport cancelling some of their flights. In this case, that would be Iberia, and it has been considered that only flights with 120 min or more of delay are cancelled. This criteria results in 24 flights being cancelled, and consequently, the slots where these flights were assigned are available. Thus, a new slot assignation is needed.

Given that Iberia is the airline that cancelled their flights, they will be given priority in the new assignation. For each empty slot available, the Iberia flight with the earliest ETA compatible with that slot will be allocated there, and the slot that the flight previously occupied will be assigned using the same criteria. This process will be repeated until all Iberia flights are assigned to their most optimal compatible slot. Once this is accomplished, the slots left empty will be offered to all other airlines following First-Come-First-Serve. The slots these other airlines leave empty will once more be offered to Iberia first and then follow the same process. The results of this scenario are the following:

	Before Cancellation	After Cancellation
Air Delay (min)	625	625
Total Delay (min)	21528	13036
Maximum Delay (min)	237	183
Unrecoverable Delay (min)	814.68	626.84

Table 1: Cancellations

As seen in Table 1, there is no variation in air delay after the cancellation, this is due to the fact that exempt flights were already assigned the most optimal slots, following GDP philosophy. On the other hand, the reduction in ground delay is very significant, as not only the delay of the cancelled flights has been eliminated, the consequent compression of slots enables other flights, mainly from Iberia, to be assigned to much better slots.

3. Ground Holding Program

3.1. Methodology

The Ground Holding Program is an ATFM technique that uses linear programming to optimize the slot allocation minimizing the cost. The MATLAB's intlinprog is minimization method chosen for the calculations, as it minimizes the value of any given function, given a set of equations and constraints. Again, the list of the flights affected by the regulation is introduced, *i.e*. the flights from 10.00 (start time) to 17.58 (very end of the regulation).The cost function to minimize is the following:

$$c_{ft} = r_f \left(t - e\left(f\right)\right)^{1+\epsilon} \tag{1}$$

Where r_f are the cost parameters, t the slot time intervals, $e(f)$ the ETAs and ϵ the parameter to account for exponential growth in costs. In the case of this project, the cost parameters applied have been extracted from a study by the University of Westminster (Dr. Andrew Cook, 2015), particularly from tables 26 and 28 for ground and and air delay, respectively. The parameters obtained in said document are time dependant; they account for the exponential increase in costs and are discretized for delays of 5,15,30,60,180, 300 minutes and over. Thus, there is no need for an ϵ parameter. Furthermore, this values are available for a wide range of commercial aircraft, and full tactical costs are considered, including passenger related; which make these parameters suitable for our study.

For this work a simplification is made and consists on making 4 groups of similar aircraft models from the affected airplanes list and assigning the value of the cost to one plane of the tables of the paper. The group of planes are shown in Table 2:

Airplanes From The Cost Table	Group of airplanes from the list
B744	B772, B77L, B773, B77W, B744, B748, A388, B752, B753
A332	A332, A333, A359,A35K, B788, B789, B78X, A342, A343, A345, A346, B762, B763, B764
B738	A318, A319, A320, A321, A19N, A20N, A21N, B738, B739, B38M, B737, E190, E195, CRJX, CRJ9
AT72	All the other planes such as private jets and small turbo-propeller planes

Table 2: Simplification groups of airplanes

Therefore, in accordance with the contents of Table 2, the costs of the groups of airplanes at the right will be assumed as the cost of the airplane from the cost table of the Westminster paper (Dr. Andrew Cook, 2015).

To conclude, additional constraints also have been added in order to obtain realistic results. In particular: not permitting negative values of delay (aircraft arriving before their ETA) and restricting the maximum air delay possible to 30 min, via the assignation of exorbitant costs to the latter cases.

4. Intermodality

4.1. Methodology

The intermodality is another ATFM technique that uses other means of transport to reduce environmental impact. It achieves its goal substituting some flights by an alternative transport such as rail, which is in fact the transport used to substitute the flights in this project.

The substitution of a flight takes place when the rail time for that specific route is less than 5 hours. The criterion significantly impacts the majority of domestic flights in this work for two primary reasons. Firstly, there are no direct international trains with a travel time of less than 5 hours. Secondly, the central location of the aerodrome enables access to nearly every major city in Spain, attributable to the fact that train travel times do not exceed 5 hours for almost every route.

The main reason why the goal of this technique is to reduce environmental impact is that for short distance routes airplanes are remarkably inefficient. This inefficiency is caused because planes are their most efficient while cruising, and, in such short routes the cruising time is short, therefore, the flights become inefficient and the environmental impact increases.

Coming back to this work, the flights that are suitable to be substituted by train are a total of 71 during the whole day while 40 of them are inside the regulation time interval (from 10.00 to 17.58). The most frequent route is Barcelona - Madrid with 21 arrivals during all the day and 10 within the regulation.

The travel times of the rail have been extracted from Chrono-Trains web (Benjamin Tran Dinh, [n.d.]). In order to compare the two means of transport, the travel times door-to-door and the carbon dioxide emissions in kilograms per passenger per kilometer will be compared for both of them. The emissions for the rail are extracted from Eco Passenger web (UIC et al., [n.d.]) and the emissions of the planes are extracted from ICAO emission calculator (ICAO, [n.d.]). In Table 3 it can be seen the routes substituted and their emissions and travel time for both rail and airplane (the data shown will be analysed in the following section):

Route	Distance (km)	Emissions g/km·pax		Travel Time Door-To-Door (minutes)	
		Rail	Plane	Rail	Plane
Sevilla	390	34.6	186.4	114	195
Málaga	415	63.3	197.1	175	210
Alicante	360	33	150.8	272	195
Barcelona	504	33	175.8	254	210
Valencia	302	32	310.6	215	205
A Coruna	506	39.5	163.4	144	205
Granada	360	38	137.2	175	195
Castellón	309	33	184.5	180	195
Santander	340	33	197.9	240	205
Bilbao	322	31	190.4	156	215
Vigo	465	43	158.9	225	210

Table 3: Rail compared to airplane: emissions and travel times

Note that the travel time is door-to-door time. For the plane, this time shall include the fly time, the check-in and security checks time and the time needed to reach the airport from the origin city downtown and vice versa for the arrival city.

To simplify the computations, the travel time from the airport to the city will be assumed as 60 minutes (30 minutes for the time between departure city and the departure airport and 30 minutes for the arrival) and the check-in and security check's time will be assumed as 75 minutes. So, summarizing up, 135 minutes will be added to the fly time to compute the door-to-door time for the airplane.

For the rail the time to reach the city from the station will be neglected. This is because most of the train stations are placed inside the cities.

4.2. *Intermodality cost reduction*

Once the suitable flights are extracted from the list of flights, one can calculate again the end time of the regulation (which is earlier than before due to the reduction on the demand) and the total cost of the delay using the cost function from GHP. It has also been calculated the GDP cost.

The time of the end of regulation with the new set of flights is 17.05. This means that there are 53 minutes less of regulation affecting the activity of the aerodrome. Therefore, the inter-modal approach helps reduce the impact of the regulation reducing it's duration. Recall that this happens because there are some flights substituted by rail so the demand to the airport is less than before.

5. Discussion

Having introduced all methodologies and applied their corresponding algorithms to the initial set of data, a series of Key Performance Indicators (KPIs) have been obtained in order to assess the performance of each of the previously mentioned methodologies. These include important values with regard to delay, cost and emissions and can be found in Table 4. Given that such amount of data has little meaning by itself, the results obtained have been organized in Key Performance Areas (KPAs), these are areas of special interest which help compare the outcomes of different methodologies and decide which is more desirable, depending on the goal to be achieved.

Before commenting the KPAs, observing Table 4 one discerns a slight variance in the total delay values between GDP and GHP. This discrepancy stems from divergent calculation methodologies. A similar phenomenon is manifest within the two inter-modal alternatives, where a comparable marginal distinction is evident. However, a substantial dissimilarity arises from a reduction in demand in the inter-modal scenarios, leading to a corresponding diminution in delays. This demand reduction is achieved through the judicious substitution of flights by rail, as expounded upon in Section 4.

5.1. *Safety*

The safety of operations depends on various factors. It is to be considered that in all 4 cases studied there is no difference between landing rates, therefore this cannot be a parameter to consider. Factors like pilot and ATC workload will be relevant, the more complex the program is to be handled, the less safe it can be considered due to human fatigue. When considering ATC, GHP can be considered less safe than GDP, as the latter's algorithm is much simpler and more straightforward, leading

Table 4: Delay, Cost and Environmental KPIs

			Delay (min)							Cost (€)					Emmissions ($kg\ CO_2$)
	Arrival Type	**Number of arrivals**	**Total**	**Average**	**Standard Deviation**	**Relative Standard Deviation**	**Maximum**	**OTP** (flights)	**Unrec.**	**Total**	**Average**	**Standard Deviation**	**Relative Standard Deviation**	**Maximum**	**Total**
GDP	**Controlled Flights**	182	20903	114.85	52.73	45.92%	237	6	-	$6.69 \cdot 10^6$	$3.67 \cdot 10^4$	$2.14 \cdot 10^4$	58.47%	$1.07 \cdot 10^5$	0
	Exempt Flights	96	625	6.51	8.51	130.68%	29	77	-	$1.17 \cdot 10^5$	$1.22 \cdot 10^3$	$2.14 \cdot 10^3$	174.95%	9495	$1.73 \cdot 10^4$
	Total	278	21528	77.43	67.12	86.68%	273	83	814.68	$6.80 \cdot 10^6$	$2.45 \cdot 10^4$	$2.43 \cdot 10^4$	99.19%	$1.07 \cdot 10^5$	$1.73 \cdot 10^4$
GHP	**Ground Delay**	182	19437	106.8	98.71	92.43%	439	24	-	$4.73 \cdot 10^6$	$2.06 \cdot 10^4$	$3.27 \cdot 10^4$	125.53%	$1.25 \cdot 10^5$	0
	Air Delay	96	2072	21.58	9.53	44.19%	30	27	-	$4.88 \cdot 10^5$	$5.08 \cdot 10^3$	$3.45 \cdot 10^3$	67.80%	$1.43 \cdot 10^5$	$5.74 \cdot 10^4$
	Total	278	21509	77.37	89.70	115.94%	439	51	800.92	$5.22 \cdot 10^6$	$1.87 \cdot 10^4$	$2.83 \cdot 10^4$	150.59%	$1.25 \cdot 10^5$	$5.74 \cdot 10^4$
GDP Inter-modal	**Controlled Flights**	137	12848	93.78	44.66	47.62%	190	6	-	$3.92 \cdot 10^6$	$2.86 \cdot 10^4$	$1.85 \cdot 10^4$	64.70%	$9.52 \cdot 10^4$	0
	Exempt Flights	88	623	7.08	8.67	122.40%	29	69	-	$1.17 \cdot 10^5$	$1.33 \cdot 10^3$	$2.20 \cdot 10^3$	165.31%	$9.5 \cdot 10^3$	$1.73 \cdot 10^4$
	Total	225	13471	59.87	55.19	92.06	190	75	585.28	$4.03 \cdot 10^6$	$1.79 \cdot 10^4$	$1.97 \cdot 10^4$	109.78%	$9.53 \cdot 10^4$	$1.73 \cdot 10^4$
GHP Inter-modal	**Ground Delay**	137	11655	85.07	72.81	85.58	336	19	-	$2.57 \cdot 10^6$	$1.87 \cdot 10^4$	$2.26 \cdot 10^4$	120.64%	$9.87 \cdot 10^4$	0
	Air Delay	88	1979	20.42	9.93	48.61%	30	29	-	$4.15 \cdot 10^5$	$4.72 \cdot 10^3$	$3.31 \cdot 10^3$	70.23%	$1.06 \cdot 10^4$	$4.98 \cdot 10^4$
	Total	225	13452	59.78	65.24	109.13	336	48	574.52	$2.98 \cdot 10^6$	$1.32 \cdot 10^4$	$1.9 \cdot 10^4$	143-46%	$9.87 \cdot 10^4$	$4.98 \cdot 10^4$

to less possibility of error and less confusion. When it comes to how intermodality can affect, these produce less regulated aircraft, therefore less ATC workload.

The other perspective to consider is the pilot's, more average air delay corresponds to more hours flown, leading to more fatigue, and therefore less safety. In this aspect, GDP can be considered more safe (the average air delay is 15 minutes lower than GHP), as it's philosophy is based on reducing air delay.

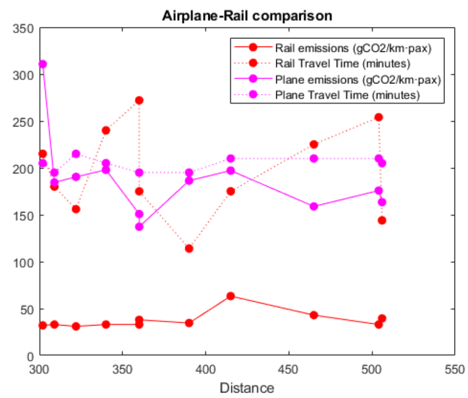

Figure 6: Rail and Airplane compared: Emissions and Travel Time

5.2. Environment

When it comes to environmental effects of the programs, it can be seen that the intermodality options are always more optimum, as can be observed in Table 3 the emissions by rail are less than those by air. Besides, Figure 6 illustrates the data from the table but in a more visual way:

In the previous figure it can be seen that the airplane emissions are much higher than the railway emissions making the intermodality alternative a good way to reduce environmental impact.

To conduct a more thorough analysis of the graph, it is noteworthy that the travel times of rail transport oscillate in relation to those of air travel. This variability complicates the determination of which mode of transportation is superior in terms of travel duration, at least with this amount of distances plotted. Notably, for certain distances, rail transportation is superior in terms of travel duration compared to air travel, while for other distances, the inverse holds true, with rail transport requiring notably less time. This phenomenon can be attributed to differences in the types of trains employed, such as the distinction between high-speed trains and their slower counterparts.

When it comes to comparing GHP and GDP modes, the expected result is found. Assuming all emissions are produced by airborne aircraft (and therefore considering ground delay does not contribute or is of considerably less order of magnitude), the methodology with most air delay will be the one that produces more environmental impact. This can be seen in the emissions data in Table 4 when comparing GDP to GHP and is the logical consequence of having one regulation based on reducing air delay versus one that optimizes cost.

5.3. Capacity

The capacity of an aerodrome determines the arrival rate and therefore the total amount of landings accepted in a day. When applying a restrictive program, this capacity is reduced by a certain value, creating higher delays and costs; for this reason it is considered of high importance.

Both ATFM management methods start from the same initial conditions, where the reduction in capacity is equal. The delay is determined by the latter and the scheduled arrivals, therefore the total amount is equal in both cases also. When considering intermodality it can be observed that the imbalance is lower, therefore in the case of having no regulation more aircraft can be accepted, but the intrinsic capacity of the aerodrome does not vary.

5.4. Operational Efficiency

This key performance area is a very wide category that aims to manage the air operations in the most safe and efficient way. It involves lots of different aspects such as punctuality or fuel efficiency, among many others.

For fuel efficiency, the best method is the GDP with intermodality because it minimizes the air delay and hence the fuel consumption of the airplanes and it substitutes some flights by rail, so the overall fuel consumption is reduced. This can be seen in the table 2 where the emissions for GDP with intermodality are the lowest ones of all of the ATFM techniques analysed.

When considering the punctuality, the way to compare the methods will be the number of flights performing an On Time Performance of each method. However, the absolute value shown in Table 5 is not representative because the total number of flights is not the same for all the methods, so, the relative measure of flights performing an OTP is the one that is used. In Table 5 shown below the relative number of flights in an OTP is showed:

Method	Relative On-Time Performance
GDP	30%
GHP	18%
GDP Inter-modal	33%
GHP Inter-Modal	21%

Table 5: Relative On-Time-Performance of each method

The method with more OTP flights percentage is the GDP inter-modal, with a 33% of the flights. This means that 1 out of 3 flights will arrive with a delay lower than 15 minutes. However, there is a clear difference between the GDP and GDP inter-modal and the other two methods. So it can be said that these two methods are better than the other ones in terms of punctuality. This can be because the is the technique with more OTP flights is the GDP. This is because the GDP aims to minimize the values of air delay and it assigns the exempt flights first, applying them a very small amount of air delay and hence, making them perform an OTP.

5.5. Predictability

It is being considered not only predictability in terms of delay but also in terms of cost. The relevant KPIs that allow for the discussion in both cases are the standard deviation and the relative standard deviation. The former is used to obtain the "width" of the normal distribution probability curve that lies intrinsic in the set of all data acquired when performing the regulation; the latter is used to obtain a "fair" comparison as it allows the visualization of the degree of deviation from the mean value, and therefore whether the distribution is "wide" or "slim" with respect to the average.

The GDP first-come-first-serve philosophy assigns exempt flights first, leading to their allocation in their optimum or near optimum slot, the controlled are assigned to the rest. For this reason it will be easier to predict the value of air delay, whereas it will be harder for ground delay. However, the amount of dispersion in air delay values compared to it's mean will be larger than that of the ground, as controlled flights with similar ETA's are mapped to slots that lie close by, leading to less dispersion and more *relative* predictability. This holds for both delay and cost, regardless of intermodality.

The GHP algorithm, on the other hand, assigns aircraft to a slot by optimizing the cost. This creates much more dispersion than in the GDP, as flights with close ETA's do not necessarily have similar slot assignations, being that it varies with the cost of delay of each particular arrival. In finding the optimum solution, the algorithm no longer maintains the same level of "order" that is achieved in the GDP, it is more chaotic and therefore less predictable both relatively and absolutely. When comparing air delay and ground delay, as the former has been limited to 30 minutes, it is logical that the amount of deviation possible will be less than that of the latter.

The effect the intermodality has on both philosophies cannot be pinned down to one reason or one answer. There are light fluctuations in the values of the relative standard deviation, while the standard deviation itself decreases due to a decrease in flights. It can be said that it is more predictable in an absolute fashion, but with respect to the mean it yields similar values, as neither philosophy for the assignation has been changed at it's core.

5.6. Cost Effectiveness

When considering Cost-effectiveness, the most relevant KPIs are those regarding cost and also emissions, since the aim of this KPA is to asses the balance between implementing measures to improve environmental performance and keeping operations financially viable.

In this regard, GHP methodology is expected to outshine GDP, as its main goal is to minimize costs. When analyzing the data, it is not trivial. It's true that overall costs are significantly lower when applying GHP, however, costs for flights with air delay are 5 times higher on average than GDP, furthermore emissions are also much higher in GHP. Naturally, Intermodal options maintain similar relations, but with lower values, given that there are less flights.

Taking all this into account, deciding the most cost-effective option rests on the weight given to each of the aspects mentioned.

5.7. Flexibility

In the case of flexibility, it is studied the ability for the program to be manipulated and changed without rendering it useless. In a certain way, stability is also being considered, as it shows what perturbations to the initial planning can occur without problems arising, or the effect that the cancellation of the whole ordeal would produce.

If the program were to be cancelled, a part of the delay is unrecoverable. Both GDP and GHP show very similar statistics in this area, therefore there is no notable difference can between them. When analysing the effect of intermodality, less flights are scheduled leading to less delay in general, and therefore less unrecoverable also, leading to a higher flexibility,

5.8. Access and Equity

It could be argued that the most important KPA in present times is access and equity. Any regulation that does not perform well when analyzed from this point of view will not be applied unless the situation is extreme and it is required. The relative standard deviation of not only delay but cost must be considered when discussing, seeing as it matters not only how much it is deviated, but how this deviation compares to the mean (the amount experienced by others), as fairness, by definition, always a relative value.

As has been stated while discussing predictability, the relative standard deviation of cost and delay for both GDP methods are very similar, and lower than that of the GHP's, leading to more overall fairness. It could be said that those airlines with more scheduled flights are affected in an unfair manner but the distribution of delay however, takes not into account the airline but only the cost of it's delays and it's ETA; therefore the distribution of delays is purely probabilistic, not biased against any specific airline. It is fair to have more overall delay and cost when more landings of the airline are occurring.

6. Summary and conclusions

In the present times, with the growth of air transport, will always be necessary to have the means to apply a regulation at an aerodrome whenever it is necessary. It is of great importance to identify what areas are critical in that specific situation, what can be sacrificed and what has to be limited or set to a specific range or value in order to obtain the most optimum solution. The latter may not always be the same even in a specific aerodrome; an aeronautical study must be performed for the specific case at hand and options must be discussed, as a great variety of conditions may have led to the necessity of regulating in the first place and these may need handling in different ways.

In the case of this study where the 4 methods described have been considered, both GDP and GHP with their respective intermodality counterparts are valid models to consider when having to apply a regulation at an aerodrome, as both GDP and GHP perform better in certain areas. The information in Section 5, can be summed up in the following manner:

- Intermodality options are more feasible than their counterparts delay wise, economically, environmentally and more flexible. It is also safer as ATC workload is reduced and more operationally efficient as this reduces air delay and therefore fuel consumption. Their effect on equity and access, predictability is negligible, seeing as the philosophy used is the same as their counter-parts.

- GHP is more efficient than GDP economically, but with more risk involved as it is less predictable, less safe (obviously above the minimum safety threshold), less fair and worse environmentally.

- Further research is needed in order to develop better ATFM methodologies which not only aim at improving a single KPA, but improve performance across all areas of the regulation.

Contributions

WP1:Data extraction: Marçal,Héctor and Ben. Coding: Marçal. Post-Process and results: Marçal

WP2: Coding: Marçal,Héctor and Ben. Post-Process and results: Marçal and Ben

WP3: Coding: Marçal, Héctor and Ben. Post-Process and results: Marçal and Ben

WP4: Data extraction: Héctor. Coding: Ben. Post-Process and results: Ben and Héctor.

Report: Marçal, Héctor and Ben

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(OpenAi, [n.d.])