Utilizing schedule buffers to reduce propagated delay

A new approach for tactical Air Traffic Flow Management slot allocation

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***Abstract*—To compensate for anticipated delays and improve on-time performance, Aircraft Operators usually embed a buffer time in their schedules strategically, but also have the flexibility to fine tune their departure times on the day of operations (tactically). In Europe, one of the instruments at the Network Manager's disposal to tackle demand-capacity imbalance is to impose ground, i.e. Air Traffic Flow Management – ATFM, delays to flights. The current practice for assigning ATFM delays does not take into account whether flights have any remaining schedule buffer to absorb ATFM delay and potentially reduce delay propagation to subsequent flights. Furthermore, the policy presently employed is to minimize ATFM delays, an order of magnitude of half a minute per flight on average, while propagated delays are approximately ten times higher. We explore the possibility to use ATFM delay as a tool to minimize delay propagated to subsequent flights, but also to increase flights' adherence to airport slots at coordinated airports.**

Keywords-Air Traffic Flow Management; schedule buffer; propagated delay; airport slot adherence; performance

I. Introduction

Airspace and airport congestion is an inherent problem in Europe, often resulting in substantial flight delays, re-routings and even cancelations. In general, congestion can be tackled from both demand and capacity side: increasing capacity to match the demand and/or managing demand according to the available capacity.

Capacity expansion is seen as a long term solution to cope with increasing demand [1]. It is associated with major costs [2], a great deal of which is passed on to airspace users, which in turn may have a negative feedback on demand [3]. There are also very limited options to increase capacity at a short notice, yet, Air Navigation Service Providers (ANSPs) have to operate flexibly to cope with various aspects of traffic variability and predictability and deliver a certain (required) level of service [1]. This usually leads to incorporating substantial and costly capacity buffers into ANSP planning decisions [4].

Therefore, a common short-term remedy to capacity shortfalls is focused on the demand side of inequality: regulating traffic demand through administrative or economic measures [5].

The Network Manager (NM), central figure of European Air Traffic Management (ATM), has a number of options at disposal to tackle demand-capacity imbalance. One of them is to apply a regulation, i.e. to limit the maximum rate of aircraft entering either a regulated volume of airspace or airport. Flights subject to regulation are assigned new take-off times, through ATFM (time) slots, and as a consequence some flights are (ATFM) delayed. The NM takes account of ANSP capability to accommodate additional demand (capacity buffers) in the process of demand-capacity balancing. However, it does not make use of potential "demand-side buffers".

Namely, Aircraft Operators (AOs) embed time buffers in their schedules with primary intention to strategically compensate for (a portion of) tactically anticipated delays, while maintaining the on-time performance of flights and the operational reliability of schedules [6]. For instance, an AO published schedule (strategic) for an airport pair could be 10:00 to 12:00, while the actual gate-to-gate time (tactical) is 1:30 only, leaving 30 minutes as a buffer. If this flight was affected only by a 30 minute ATFM departure delay, it would still arrive on time since ATFM delay is 'absorbed' within strategically allocated buffer and is not propagated to the subsequent flight.

This study examines the possibility to systematically use (remaining) schedule buffer to minimize propagated delay to subsequent flights caused by ATFM delay. We propose a model for the ATFM slot allocation process and an algorithm to further improve airport slot adherence at slot coordinated airports. The objective of this initial research is to account for stakeholders' different perspectives of congestion problem, in terms of business and operational needs, and bring the proposed methodology closer to dealing with real-life instances of the problem.

Before the framework for modelling and formalization of model is explained (Section III), a background of congestion problem in Europe is provided in Section II, focusing on

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different perspectives of delays. Numerical example and results are then presented (Section IV), followed by discussion and conclusions (Section V).

II. Background

A. *The scope of delays in Europe*

Much like a single unit of airspace (sector) is capacity constrained due to safety reasons and required level of service, a number of airports in Europe have airport capacity strategically capped through airport slots (coordinated airports). AOs negotiate and obtain airport slots six months in advance, usually aligning airport slot times with the published schedule times of departure (*STD*) and arrival (*STA*) [7]. AOs are obliged to submit ICAO flight plans (FPL) to the NM, indicating, among else, desired route to be flown and estimated off-block time (*EOBT*). The NM systems then calculate estimated take off time (*ETOT*) and flight profiles, i.e. trajectories in space and time. FPLs are mostly filed on the day of operation (tactically), based on which loadings of ATC sectors are calculated. When expected demand exceeds available sector capacity, affected ANSP may request a regulation. For a regulation, an ATFM slot list is defined based on a regulation duration and rate. Flights entering a regulated location during the regulation period are subject to that regulation and are assigned ATFM slots based on First Planned First Served (FPFS) principle, using Computer Assisted Slot Allocation (CASA) system. FPFS basically means that a flight which is planned to enter the regulated location earlier has priority over flights intended to use it later (based on estimated time over (*ETO*) the regulated location). ATFM delay is calculated for each regulated flight as the time difference between ETO and earliest time available to enter the regulated location. ATFM delay is then added to EOBT, and new off-block and take-off times are calculated, COBT and CTOT, respectively.

The NM reports 0.61 minute per flight average en-route ATFM delay in 2014, for the total traffic of 9.6 million flights, of which 3.2% were affected by ATFM en-route delays [1]. The delay is far from uniformly distributed: 1.6% of flights were delayed by more than 15 minutes due to ATFM regulations [1]. Longer delays are main contributors to airline delay costs, since a minute of longer delay costs more than that of a short one [8]. On the other hand, Central Office for Delay Analysis (CODA) in Eurocontrol reports that AOs experienced 0.4 minute per flight average en-route ATFM delay in 2014 [9]. This discrepancy may arise from both different perspective of delay and different methodology used to measure it: the NM calculates planned departure delays, while AOs account for ATFM delay they have actually experienced at departure.

On the other hand, primary delays (FIGURE 1), i.e. delays due to ATFM regulations, weather, etc., accounted for 5.4 minute in 2014 [9]. Reactionary delays, also known as 'knock-on' or 'propagated delays' are delays which are transferred from a previous flight of the same (rotational) or a different (non-rotational) aircraft (generally resulting from primary delays). Reactionary delays added 4.3 minutes more to sum up to total of 9.7 minutes average delay per flight from all-causes [9]. Average all-cause delay per delayed flight was 26 minutes [9].

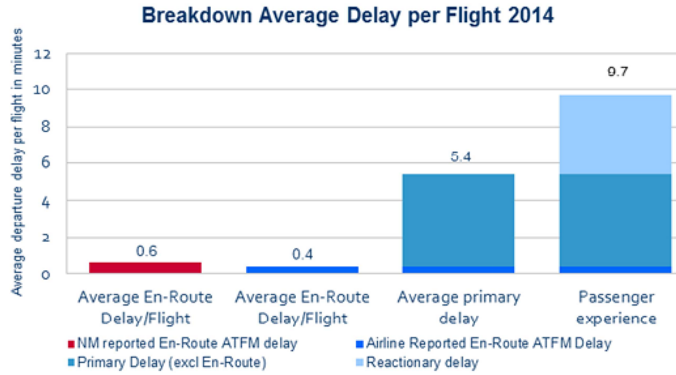

Figure 1. Different perspectives of delay in Europe (*source* [9])

B. *Performance driven decision-making*

To support, inter alia, on-time operations, European Commission launched the Single European Sky (SES) initiative aiming at the modernization of Europe's ATM to provide better services [10]. SES high level (political) goals are expressed and interpreted through the strategic performance objectives for four Key Performance Areas (KPAs): safety, capacity, environment and cost-efficiency. Achieving SES high level goals is performance-driven, while progress is monitored through Key Performance Indicators (KPIs) and benchmarked against SES Performance Targets laid down in SES Performance Scheme ([11], [12]). One of the binding performance targets for the NM and ANSPs is the average en-route ATFM delay per flight, adopted as the KPI for 'capacity' KPA [13]. There are no airport-related performance targets at the network level presently.

ANSPs are therefore expected to meet the imposed SES Performance Scheme ATFM delay targets. This is one of the drivers in their operational decision making process, leading sometimes, for instance, to mandatory re-routing of flights to avoid excessive ATFM delays [14]. On the other hand, AO unsurprisingly argue that they should be in a position to choose between re-routing and accepting a delay; from their perspective, re-routings are merely seen as an instrument to bring down ATFM delay figures to meet ANSP delay targets [15].

Further, AOs have already raised a concern regarding the delay metrics used in SES Performance Scheme since those focus on ATFM delay which is of different order of magnitude compared to actual all-cause delay [16]. Cook [7] states that much of the focus of delay management is on the ATM process, since its administrative measures are easily adoptable and mathematically modellable, but leaves open to debate if this focus is misplaced. Performance Review Commission [1] states that a better understanding of ATM contribution towards propagated delays is needed, as well as to identify potential strategies to deal with the delay propagation. The main question is how the current FPFS policy, which minimizes total ATFM delay of regulated flights (the NM perspective) [17], affects an order of magnitude higher primary and consequently, reactionary delays (AO perspective). One could argue that the latter is primary concern for AO business, while the former is binding for ATM, resulting in divorced delay phenomenon perspectives.

C. Previous contributions and a way forward

Castelli et al. [17] propose a market-based slot allocation to minimize the overall cost of delay and demonstrate benefits of such approach using real-life morning en-route sector regulation and CASA slot allocation as benchmark. They also show that current approach minimizes ATFM delay and argue that a different (optimal) slot allocation is available in the cost domain, i.e. when aspects other than delay duration are considered too. Likewise, our model builds on CASA and uses it as a benchmark, with the difference that we stay in 'delay domain', i.e. we minimize propagated delay, rather than delay cost per se. With such an approach it is arguably easier to follow the logic behind the model and directly compare results against the current policy [18]. Though it is more likely for an AO to evaluate its decision based on costs, flow manager decides using time as a criterion [19].

Vranas et al. [20] used ground slack to limit coupling of consecutive flights, a common constraint in so called Multi-Airport Ground Holding Problem [21], accounting indirectly for excessive delay due to late arrivals in the objective (cost) function. They found that optimal solutions with and without coupling constraint are almost the same when all flights have the same cost function, which is an unrealistic, but long-established practice of Federal Aviation Administration in the US. Bertsimas et al. [22] consider two coupling constraints: connectivity at airports and connectivity in sector, but do not consider schedule buffers per se. These papers address network-wide instances of congestion problem, focusing on mathematical modelling and computational times [23]. Our research, on the other hand, demonstrates applicability of proposed methodology using a small-scale example of en-route sector congestion problem in Europe. We propose a binary integer programming (BIP) model to solve it. Similarly, Tosic et al. [24] proposed a BIP model to solve an en-route sector capacity shortfall, by minimizing cost of ground delays and re-routings.

The first empirical analysis of reactionary delays and their scope in Europe [25] revealed that reactionary delays starting in the morning have the highest impact on subsequent flights. On average, every minute of primary delay (e.g. due to ATFM regulation) causes 0.8 minutes of propagated delay [1]. Therefore, we focus on morning en-route regulations to alleviate this phenomenon. Cook et al. [26] proposed passenger-centric delay metrics, while the recent paper of same authors compares, among else, flight and passenger-centric perspective of reactionary delays under different prioritisation and scenario settings [27]. They found that assigning departure times based on cost minimisation also improved a number of passenger delay metrics, but at the expense of increased reactionary delay.

We also address practical issue of adherence to airport slots of regulated flights and demonstrate how to select flights to be (further) delayed, so as to improve airport slot adherence. Etxebarria et al. [28] simulate different prioritisation strategies at a network level, one of them being priority for flights flying to congested airports, but found no benefits compared to FPFS policy. Our approach is rather focused on a specific local problem and is very well aligned with the new SESAR (SES ATM Research) concept 'Short-Term Air Traffic Flow and Capacity Management Measures' (STAM), which has already passed the trial stage [29].

III. Binary Assignment Optimization-Based Model

A. Modelling framework

Presently, the cost of strategically allocated buffer (time) is much lower to AOs than the cost of tactical delay [1]. Moreover, delay propagation starts in the morning and postponing this early start might lower total delay at the end of the day [9]. AO focus on schedule adherence in the morning [25] and assuming that majority of early rotations still have schedule buffers at large [30], it is reasonable to test proposed methodology for an early morning regulation.

More than 10% of flights in Europe arrive more than 15 minutes ahead of schedule [9]. Major reasons for early arrivals are longer schedule buffers and more direct routings once flights are airborne, but there is still a share of flights (1%) departing 15 minutes ahead of schedule [9]. Flexibility to tactically shift desired take-off time much earlier than strategically planned could also cause congestion problems at airports already operating at their capacities [9]. Targeting these 'early filers' could improve airport slot adherence. Similarly, for regulated flights with excessive schedule buffers, flow manager could impose additional ATFM delay to bring them closer to their airport slot times, thus increasing predictability without generating any propagated delay.

B. Assumptions and model formalization

Consider an en-route sector regulation R, starting at R_{Start} and ending at R_{End} (measured in hours and minutes), with a rate C_R defined as a number of flights per hour (notation is similar to that in [17]). Number of ATFM slots with capacity of one flight is then calculated as:

$$N_S = C_R \cdot (R_{Start} - R_{End}).$$

ATFM slots $S = \{1, \dots, N_S\}$ are defined with their start time L_i and end time U_i, where

$$L_i = R_{Start} + (i-1)/C_R,\ i \in \{2, \dots, N_S\},\ L_1 = R_{Start}$$

$$U_i = L_i + 1/C_R - 1, \text{ for } i \in \{1, \dots, N_{S-1}\},\ U_{N_s} = R_{End}$$

In practice, regulations are inherently dynamic and any of the parameters could change between the moment of regulation activation and R_{End} (regulation could even be cancelled). We assumed that once defined and applied, the regulation remain as is.

Based on filed FPL and calculated flight profile, the NM's FPL processing system estimates time over (ETO_f) the regulated location for each regulated flight $f \in F^R$, where F^R is a set of regulated flights. A list of feasible ATFM slots for a flight f is a subset of the slot list S defined as $S^f = \{i: ETO_f \leq U_i\}$, i.e. a flight can be assigned to any slot which ends after the estimated time over the regulated location.

We assume the realization of flights as planned, without flights' cancelation. For each flight, we randomly assign schedule buffer SB_f. Note that strategically planned schedule buffer could be tactically increased by filing *EOBT* earlier than STD or decreased if the flight is already delayed.

ATFM delay d_{fi}^A and propagated delay d_{fi}^P for each flight are calculated ($\forall f \in F^R, \forall i \in S^f$), respectively,

$$d_{fi}^A = \max(ETO_f, L_i) - ETO_f$$

$$d_{fi}^P = \begin{Bmatrix} 0, \max(ETO_f, L_i) - ETO_f - \text{SB}_f \leq 0 \\ \max(ETO_f, L_i) - ETO_f - \text{SB}_f, otherwise \end{Bmatrix}$$

If a delayed flight f still arrives earlier than scheduled, it does not generate propagated delay to the next flight, therefore d_f^P is set to zero. We assume that ATFM delay is the only delay flights experience on departure without any primary or reactionary delays from previous flights.

Let x_{fi} be a binary decision variable, which takes value 1 only if a flight f is allocated to slot i and 0 otherwise. Minimizing propagated delay (MINP) is now assignment problem formulated as follows.

Minimize

$$min \sum_{f \in F^R} \sum_{i \in S^f} d_{fi}^P x_{fi} \tag{1}$$

Subject to

$$\sum_{f \in F^R i \in S^f} x_{fi} \leq 1 \tag{2}$$

$$\sum_{i \in S^f} x_{fi} = 1, \forall f \in F^R \tag{3}$$

$$x_{fi} = 0 \lor 1, \forall f \in F^R, \forall i \in S^f \tag{4}$$

Objective function (1) seeks optimal assignment of regulated flights to ATFM slots to minimize propagated delay. Note that replacing d_{fi}^P with d_{fi}^A ATFM delay is minimized. Constraint (2) prevents assigning more than one flight to a single ATFM slot, while (3) ensures that all the regulated flights are allocated to one ATFM slot. Last constraint (4) limits the decision variable to 0-1 values only.

This methodology stands for flights subject to one regulation only; the case considered in this study. Flights subject to multiple regulations are assigned ATFM delay of the most penalizing regulation and are forced through other regulations with the most penalizing delay [14].

Some regulated flights could be further delayed to improve airport slot adherence at a coordinated airport(s), assuming the airport would benefit from such a measure. We define airport slot adherence for a flight as the difference between tactically and strategically planned flight times, assuming that airport slot and published schedule coincide. For a regulated flight departing from a slot coordinated airport, airport slot adherence (a_f) is defined in a similar manner as

$$a_f = STD_f - CTOT_f,$$

where *CTOT* is calculated take-off time, i.e. *ETOT* with added ATFM delay based on the allocated ATFM slot i

$$CTOT_f = ETOT_f + d_{fi}^A.$$

For a regulated flight arriving at a coordinated airport, a_f is defined as

$$a_f = STA_f - CTA_{f,}$$

where *CTA* is calculated time of arrival, i.e. estimated time of arrival plus ATFM delay

$$CTA_f = ETA_{f,} + d_{fi}^A.$$

We observe a_f in absolute terms: the lower a_f, the higher airport slot adherence, as flights depart or arrive closer to planned schedules. An approach to increase airport slot adherence (APSA) is proposed.

After a slot allocation (1) – (4) is carried out, a list of flights subject to en-route sector regulation operating to/from a selected coordinated airport is created. From the list, regulated flights remaining a buffer time (r_{fi}^P) in their schedule are considered, i.e. all the flights $f \in F^R$, satisfying $r_{fi}^P = SB_f - d_{fi}^A > 0$, where i is the ATFM slot allocated to the flight f. These flights are sorted in descending order of a_f. For the flight with highest a_f we increase ATFM delay (discretely, by elementary time unit), minding that a flight cannot overtake already allocated ATFM slot, to lower a_f until one of the following conditions is met, in the following order of priority:

1) no schedule buffer remains for the flight: $r_{fi}^P = 0$ or
2) airport slot adherence is maximized for that flight $a_f = 0$ or
3) any additional ATFM delay will lead to moving the flight to already allocated ATFM slots.

The same procedure is carried for all the remaining flights in the list. All the flights with remaining buffer are sorted in the descending order of a_f, and the process is repeated until at least one of the conditions is met for all the flights considered. Note that some of the regulated flights with remaining schedule buffer could be moved to another free ATFM slot, freeing the initially allocated ATFM slot (note that optimality of (1)-(4) still holds). We test the model (MINP and APSA) on a realistic example of en-route sector regulation and benchmark results against CASA simulated slot allocation.

IV. EXPERIMENT

Demand consists of 18 flights flying over an en-route sector between 08:00 and 10:00 in the morning (TABLE 1). We use asterisk (next to the flight number, first column) to mark flights arriving to the coordinated airport operating at a capacity level. Half of the flights (*OP* column, TABLE 1) are Hub&Spoke (H&S), one third are Low Cost Carriers (LCC) and the rest are Point to Point (P2P) [25], making shares very well in line with the reported ones [1]. Average schedule buffer for LCC flights is 5 minutes, for H&S 3 minutes and 2 minutes for P2P [25]. Between 20% and 30% of all flights didn't have schedule buffers, i.e. their gate-to-gate time is longer than published schedule [25].

We assume uniform distribution $U[a,b]$ of *SB* per each of three different flight operations to realistically replicate findings in [26]:

- U[-5min, 15min], for LCC flights,
- U[-4min, 10min], for H&S flights and
- U[-3min, 7min], for P2P flights.

One realization of random number generation of *SB* is presented in (TABLE 1). Let further assume that all the flights filed their *EOBT* in line with *STD*, except the flight number 17 with its *EOBT* 20 minutes before *STD*, tactically increasing otherwise 'negative' schedule buffer. At the end, estimated time over (*ETO*) the en-route sector is associated with each flight and flights are sorted in ascending order of *ETO*.

Suppose that the initial sector capacity of 20 flights per hour is reduced to 10 for 2 hours, between 08:00 and 10:00. Two hour long regulation is applied with the rate of 10 flights per hour; based on this ATFM slot list with 20 slots and their start and end times is defined (TABLE 1).

To simulate CASA slot allocation and FPFS policy, we have to assume that FPLs for all the flights are filed well in advance without any late changes or updates. Namely, CASA slot allocation is a dynamic process and FPFS policy applies during the pre-allocation stage when slots could be overtaken based on *ETO*. After a specified time, each pre-allocated ATFM slot is allocated to that flight and cannot be taken by another flight based on *ETO* [14]. After allocating ATFM slots to flights using CASA simulated process, we calculate both ATFM (d_{fi}^A) and propagated (d_{fi}^P) delay for each flight. Then we run a model to minimize propagated delay (MINP), and APSA algorithm to improve airport slot adherence.

For this case, MINP found optimal solution to be 110 minutes in total, while sum of propagated delay for CASA is 125 minutes. As a rule, flights with longer buffers obtained later slots, as they could absorb more ATFM delay, while flights with smaller or negative buffers are moved up in the slot list. On the other hand, total CASA ATFM delay is lower than the one calculated for MINP. Note however that MINP could have multiple optimal solutions, and while propagated delay is minimized, calculated ATFM delay based on optimal slot assignment could vary. We further compare results from CASA and MINP using 30 different random samples from the same schedule buffer distributions. For this particular traffic demand and capacity constraints, MINP could save above 5% of delay propagated to subsequent flights compared to CASA. Only in two instances there were no savings, i.e. total propagated delay was the same for both models, while maximum saving was 15% (16 minutes).

We run APSA to demonstrate the improvement of slot adherence of arrivals at slot coordinated airport operating at a capacity level. In this case, airport slot adherence was improved with APSA (21 minutes) compared to MINP (38 minutes) and CASA (43 minutes). This improvement comes at the expense of additional ATFM delay imposed to flights with extra buffer time after the slot allocation (flights 1, 16, 17 and 18 in TABLE 1). Flights 2 and 3 could not further improve their airport slot adherence due to lack of additional buffer time. Note that it was also possible to 'cherry pick' flight 17 and delay it initially for 16 minutes, without propagating any additional delay. Doing so would also move the flight after R_{End} ($ETO_{17} = 09:45 + 00:16 = 10:01$) freeing one ATFM slot (S19).

V. DISCUSSION AND CONCLUSIONS

For the regulation and traffic demand considered, propagated delay savings depend on the schedule buffer distribution. There are numerous combinations of different realistic situations to be tested, but one could draw on the actual regulation statistics and come up with a few typical groups (clusters) of regulation and typical traffic mix (for a certain region) to test the benefits of model in different circumstances. Also, one could consider different schedule buffer distributions across different flight operations.

We presented an approach to increase airport slot adherence at one coordinated airport, but there is also a possibility to carry out optimisation seeking for maximizing adherence to airport slots for all the coordinated airports. As expected, with longer schedule buffers there is more room for airport slot adherence improvement. Our methodology could also be used for airport regulations as well. For further research, fine tuning of take-off times could be considered as well, reaching beyond ATM planning phase and considering ATC execution phase, like in [31].

TABLE 1. DEMAND, CAPACITY, SLOT ALLOCATION (CASA, MINP, APSA) AND RESULTING DELAYS

Flights							**ATFM Slots**		**Slot Allocation**			**CASA**			**MINP**			**APSA**		
F	***OP***	***STD***	***EOBT***	***ETA***	***STA***	***ETO***	***S***	***L-U***	***CASA***	***MINP***	***APSA***	d_{fi}^{A}	d_{fi}^{P}	a_f	d_{fi}^{A}	d_{fi}^{P}	a_f	d_{fi}^{A}	d_{fi}^{P}	a_f
1^{A}	H&S	07:10	07:10	09:41	09:50	08:06	S1	08:00-08:05	S2	S2	S3	0	0	9	0	0	9	5	0	4
2^{A}	P2P	07:40	07:40	09:55	10:00	08:18	S2	08:06-08:11	S4	S5	S5	0	0	5	6	1	6	6	1	6
3^{A}	LCC	07:20	07:20	09:52	10:05	08:20	S3	08:12-08:17	S5	S7	S7	4	0	9	16	3	3	16	3	3
4	H&S	07:30	07:30	11:24	11:20	08:21	S4	08:18-08:23	S6	S4	S4	9	13	-	0	4	-	0	4	-
5	H&S	08:00	08:00	12:40	12:40	08:30	S5	08:24-08:29	S7	S6	S6	6	6	-	0	0	-	0	0	-
6	LCC	07:50	07:50	11:00	11:00	08:39	S6	08:30-08:35	S8	S9	S9	3	0	-	9	1	-	9	1	-
7	H&S	07:45	07:45	12:03	12:00	08:43	S7	08:36-08:41	S9	S8	S8	5	8	-	0	3	-	0	3	-
8	P2P	08:10	08:10	11:31	11:25	08:45	S8	08:42-08:47	S10	S11	S11	9	3	-	15	9	-	15	9	-
9	LCC	07:30	07:30	09:53	09:55	08:47	S9	08:48-08:53	S11	S10	S10	13	11	-	7	5	-	7	5	-
10	H&S	08:15	08:15	11:00	11:10	08:52	S10	08:54-08:59	S12	S13	S13	14	4	-	20	10	-	20	10	-
11	P2P	08:00	08:00	11:03	11:00	08:53	S11	09:00-09:05	S13	S12	S12	19	22	-	13	16	-	13	16	-
12	H&S	07:40	07:40	10:53	10:50	08:59	S12	09:06-09:11	S14	S14	S14	19	16	-	19	16	-	19	16	-
13	LCC	08:10	08:10	11:04	11:05	09:03	S13	09:12-09:17	S15	S15	S15	21	20	-	21	20	-	21	20	-
14	LCC	08:30	08:30	12:08	12:10	09:10	S14	09:18-09:23	S16	S16	S16	20	18	-	20	18	-	20	18	-
15	H&S	08:00	08:00	11:45	11:50	09:27	S15	09:24-09:29	S17	S17	S17	9	4	-	9	4	-	9	4	-
16^{A}	H&S	08:20	08:17	11:17	11:20	09:41	S16	09:30-09:35	S18	S18	S18	1	0	2	1	0	2	3	0	0
17^{A}	LCC	07:50	07:30	11:34	11:50	09:45	S17	09:36-09:41	S19	S19	S19	3	0	13	3	0	13	8	0	8
18^{A}	H&S	07:40	07:40	11:21	11:30	09:50	S18	09:42-09:47	S20	S20	S20	4	0	5	4	0	5	9	0	0
							S19	09:48-09:53	Sum Delay Minutes			159	125	43	163	110	38	180	110	21
							S20	09:54-09:59												

We assume that all the regulated flights propagate the delay to subsequent flights. Although unlikely for the morning flights, some of the flights might not even have any other leg after the first one. Further, [25] founds that some flights could recover delay in the turnaround phase (Hub&Spoke mostly), which is also not accounted for by the model. To include the next leg into analysis, one would have to comprise uncertainties that go along. This would consequentially lead to encompassing and execution phase of flights (ATC), as well as turnaround process, along with the planning phase (ATM).

Assumption for schedule buffer levels in the morning hours seems realistic and AOs could benefit, in terms of propagated delay savings and adherence to their schedules, by employing methodology proposed. However, as the total delay builds up through the day and there is hardly any flexibility in schedules to absorb accumulated delays, it is not clear if the proposed methodology would always be beneficial to AOs. For the late afternoon connections, AOs try to prioritize connecting passengers [25] and perhaps passenger-centric methodology for delay assignment proposed in [32] would better answer AO needs.

Further, it is a question how MINP policy would affect scheduling practices of AOs. It usually takes one or two (IATA) seasons for AOs to adapt their schedules to compensate for anticipated pattern of delays [9]. On a related matter, a recent study [30] compares, from passengers' perspective (welfare), cases where AOs are free to decide on schedule buffer levels and a situation where a social planner would control for time schedule. They found that there are some benefits, from social point of view, if schedule buffers are decreased. In that context, we digress and briefly reflect on equivalent ATC buffers and propose a common view on the issue of buffer costs which could further be explored.

On one hand, ANSPs plan their capacities weeks and months in advance, with only very limited (and costly) possibilities to adjust those (especially upwardly) on a short notice, i.e. days in advance of the day of operation [33]. On the other hand, AOs attach great value to their flight planning flexibility and tend to make their route choice decisions (submit FPL) typically only several hours before the time of departure [34]. There is thus a mismatch between the predictability for ANSPs and flexibility for AOs, which effectively results in substantial (and costly) capacity buffers built into ANSPs planning decisions as well [4]. The key challenge therefore seems to be how to timely coordinate and align demand and capacity side decisions (predictability for ANSPs *vs.* flexibility for AOs) to reduce buffer costs on both sides of inequality and incentivize more cost-efficient outcome.

As a rule, MINP model penalizes flights with excessive schedule buffers and rewards those with less or none strategically planned buffer time, which could raise equity concerns. In our test cases, efficiency (propagated delay minutes and airport slot adherence) and equity (ATFM delay distribution) are in conflict. This trade-off is addressed in the literature already; for further research one could think of balancing between equity and efficiency by including both components in the objective function [35] or of bi-level approach maximizing efficiency first and equity second [36]. On the other hand, equity might also be seen as largely a matter of perception [35] so MINP could be seen as a strategy to prevent ATFM delays being imposed to flights already behind their schedules. Instead, ATFM delay could be distributed over a set of flights still having buffer in their schedules. Optionally, flights with significant tactical buffers could be ‘cherry picked’ to improve predictability at coordinated airports, an option AOs are open to [15]. For a minor schedule disturbance due to ATFM regulation, AOs might delegate the NM to make a decision on their behalf or in line with User Driven Prioritisation Process [10]. In case of major network disturbance and extensive delays, Collaborative Decision Making process with stakeholder consultation might be a better solution (having in mind limited resources, e.g. staff available).

Lastly, MINP strategy effectively increases average ATFM delay and, as such, might not, at least not instantly, be seen positively from the NM and ANSPs, having in mind the SES ATFM delay targets. Namely, the NM employs significant resources to contribute to en-route ATFM delay savings. In 2014, for instance, the direct NM contribution was almost one million minutes of ATFM en-route delay savings (0.09 minute per flight on average), out of which 150000 minutes of delay reduction was achieved via more direct routings [37]. On the other hand, the number of mandatory (longer) re-routings more than doubled during the last three years: 2076, 3371 and 5226, in 2012, 2013 and 2014 respectively (ATFM regulations data available via the NM ATFCM statistics service at the OneSky Online Extranet EUROCONTROL portal). These numbers partially support AO concerns (see II.B) that re-routings are used by ANSP primarily to save ATFM delay minutes and meet the SES Performance targets. Indeed AO were confronted with more mandatory re-routings, but from the ATM/C perspective, these re-routings might be seen as a measure to prevent increased traffic complexity in some regions or merely a consequence of some other factors, such as the closure of Ukrainian airspace in 2014 [1]. To that end, one natural extension of this research could deal with finding the right (or at least workable) balance between the confronted objectives of various stakeholders involved, including possibly an appropriate adjustment of associated SES performance targets.

Initial results arising from this numerical example show that it might be possible to use proposed methodology to lower delay propagated to subsequent flights and at the same time to improve airport slot adherence. This improvement usually comes at the expense of increased ATFM delay. The results therefore imply that the current regulatory settings, namely binding European ANSPs through the SES Performance Scheme, to meet ATFM delay targets might not necessarily be adequate to AOs.

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