Transportation Research Part A 95 (2017) 183–197

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Air Traffic Flow Management slot allocation to minimize propagated delay and improve airport slot adherence

Nikola Ivanov [a], Fedja Netjasov [a,*], Radosav Jovanović [a], Stefano Starita [b], Arne Strauss [b]

[a] University of Belgrade - Faculty of Transport and Traffic Engineering, Vojvode Stepe 305, 11000 Belgrade, Serbia
[b] Warwick Business School, University of Warwick, Coventry CV4 7AL, United Kingdom

ARTICLE INFO

Article history:
Received 4 January 2016
Received in revised form 26 October 2016
Accepted 7 November 2016

Keywords:
Air Traffic Flow Management
Schedule buffer
Propagated delay
Airport slot adherence
Performance targets

ABSTRACT

In Europe, one of the instruments at the Network Manager's (NM) disposal to tackle demand-capacity imbalance is to impose ground, i.e. Air Traffic Flow Management (ATFM), delays to flights. To compensate for anticipated delays and improve on-time performance, Aircraft Operators usually embed a buffer time in their schedules. The current practice for allocating ATFM delays does not take into account if flights have any remaining schedule buffer to absorb ATFM delay and 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, while propagated delays are approximately ten times higher. In this paper, we explore the possibility to control ATFM delay distribution in a way so as to minimize delay propagated to subsequent flights, but also to increase flights' adherence to airport slots at coordinated airports. To this aim, we propose a two-level mixed-integer optimization model to solve en-route demand-capacity imbalance problem and further improve airport slot adherence. The rationales behind the research are drawn from practical experience, while the model proposed is compatible with the one currently being used by the NM, making it easy to implement. We test the model on two real-world case studies and conduct ex post analysis to test the effects of violation of model assumptions on results. The results show that it is possible to use the proposed methodology to lower delay propagated to subsequent flights and at the same time to improve airport slot adherence. In addition, they suggest that the current regulatory settings aiming to minimize ATFM delay minutes, as well as operational implementation thereof, are neither necessarily fully aligned with the desires and operating goals of Aircraft Operators, nor they improve the predictability of operations in the network.

1. Introduction

Airport and airspace congestion is an inherent problem in Europe, often resulting in substantial flight delays, re-routings and even cancelations (EUROCONTROL PRC, 2015). Congested airports aim to strategically (six months in advance) establish demand-capacity balance through airport slots, i.e. by allotting predefined time periods for an aircraft to land or take-off (Cook, 2007). The central figure of European Air Traffic Management (ATM), the Network Manager[1] (NM), also has a process

* Corresponding author.
E-mail addresses: n.ivanov@sf.bg.ac.rs (N. Ivanov), f.netjasov@sf.bg.ac.rs (F. Netjasov), r.jovanovic@sf.bg.ac.rs (R. Jovanović), stefano.starita@wbs.ac.uk (S. Starita), arne.strauss@wbs.ac.uk (A. Strauss).
[1] Eurocontrol was nominated as the Network Manager for the Single European Sky via a Commission Decision on 7 July 2011 (C(2011)) 4130 final).

http://dx.doi.org/10.1016/j.tra.2016.11.010
0965-8564/

in place to proactively align air traffic demand with available airspace and airport capacity (EUROCONTROL NMOC, 2016). The NM strategic planning for a day of operations starts several months in advance, involving collaboration between Air Navigation Service Providers (ANSPs), as local or regional ATM and Air Traffic Control (ATC) units, airports and Aircraft Operators (AOs). Regardless of timely planning, majority of congestion problems get resolved on the day of operations (tactically) by means of demand management (DM) measures (Jovanović et al., 2014). One of the usual Air Traffic Flow Management (ATFM) measures 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, in an automated process using Computer Assisted Slot Allocation (CASA) system. Some of the regulated flights are delayed on the ground (ATFM delay), to temporally spread the demand to align it with the capacity available (for details, see Cook, 2007). In case of a single capacity-constrained resource, Castelli et al. (2011) show that the First Come First Served[2] (FCFS) principle applied in CASA 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. The latter stands when ATFM delay is considered solely, that is, observed and measured 'tactically' from the NM perspective.

On the other hand, different AOs may perceive the same ATFM delay in a different manner. Namely, AOs embed time buffers (slack or padding) in their schedules (Fig. 1), 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 (Wu, 2005). 'Strategic' flight time includes gate-to-gate time plus schedule buffer and as such is advertised by AOs; at slot coordinated airports strategic schedules are usually aligned with airport slots (Cook, 2007). 'Tactical' flight time accounts for the gate-to-gate time only; this information for a flight becomes available when AO submits a flight plan (FPL) to the NM, usually on the day of operations. AOs also have the flexibility to shift their tactical departure times before strategic ones, thus increasing strategically allocated buffer.

The important property of schedule buffer is that it can absorb departure delay to a certain extent and reduce delay propagation to subsequent flights (AhmadBeygi et al., 2008). CASA does not take into account if regulated flights have any (remaining) schedule buffer to absorb ATFM delay and thus prevent potential delay propagation to subsequent flights. This research primarily examines the possibility to systematically utilize schedule buffers in the ATFM slot allocation process to reduce delay propagation to subsequent flights. At the same time, we aim to align tactical and strategic schedules at slot coordinated airports to improve airport slot adherence to protect scarce capacity resources of affected airports. We propose a two-level mixed-integer optimization model for ATFM slot allocation to minimize delay propagation at the first level, and finding a solution which maximizes airport slot adherence at the second level. The objective of the 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-world instances of congestion problem.

Before the framework for modelling and formalization of model is explained (Section 3), a background of congestion problem in Europe is provided in Section 2, focusing on different delay perspectives and the present issue of adherence to airport slots. The model is tested using the real-world data and results are presented in Section 4, followed by discussion and proposed directions for further research (Section 5). We draw conclusions in Section 6.

2. Background – policy and practice

2.1. Different delay perspectives and resulting implications

The NM reports 0.61 min average en-route ATFM delay per flight in 2014, for the total traffic of 9.6 million flights, of which 3.2% were affected by ATFM en-route delays (EUROCONTROL PRC, 2015). Central Office for Delay Analysis (CODA) in Eurocontrol reports that AOs experienced 0.4 min en-route ATFM delay per flight in 2014 (EUROCONTROL CODA, 2015). This discrepancy may arise from both different perspective of delay and different methodology used to measure it: the NM calculates planned departure delay, while AOs account for ATFM delay they have actually experienced at departure (EUROCONTROL CODA, 2015). On the other hand, primary or root delays, i.e. delays due to ATFM regulations, weather, etc., were 5.4 min in 2014 (EUROCONTROL CODA, 2015). 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 min more to sum up to total of 9.7 min average delay per flight from all-causes (EUROCONTROL CODA, 2015). Although of different order of magnitude, ATFM delay comprises a share in primary, thus propagated delay, and Eurocontrol Performance Review Commission - PRC (2015) aim to better understand the ATM contribution towards delay propagation, as well as to identify potential strategies to deal with it. We provide a brief insight into regulatory environment to better grasp the drivers for operational decision making of ANSPs and the NM regarding ATFM delays.

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 (SESAR Consortium, 2012). SES high level (political) goals are expressed and interpreted through the strategic performance objectives for four Key Performance Areas (KPAs): safety,

[2] FCFS basically means that a flight which is planned to enter the regulated location earlier has priority over flights intended to use it later (for details, see Cook, 2007).

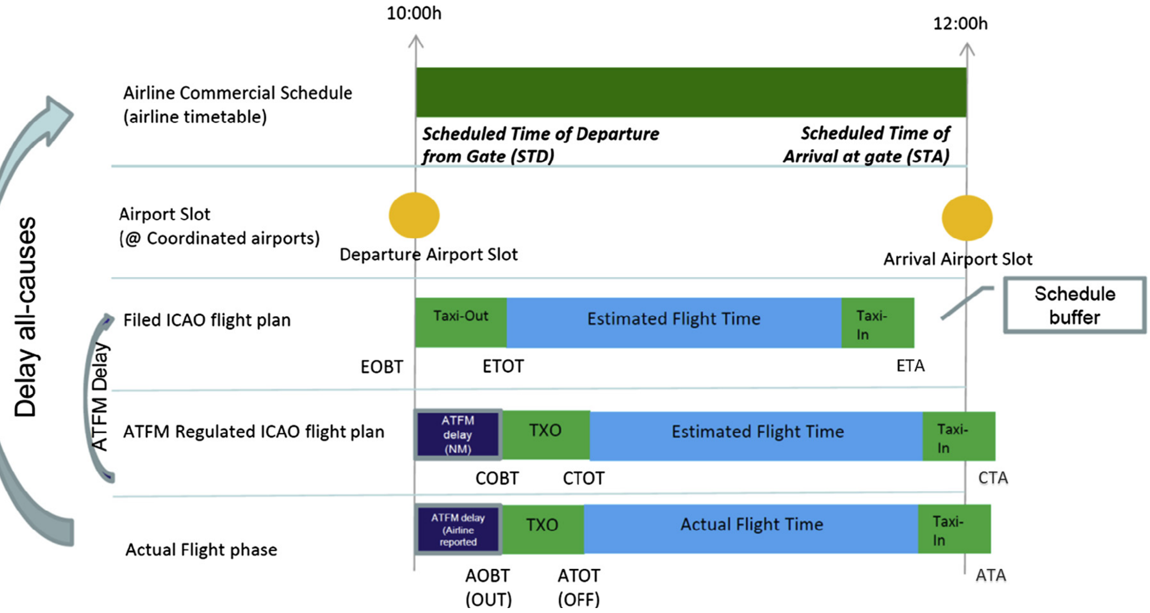

Fig. 1. Flight planning timeline (adapted from Wandeler, 2014.).

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 (European Commission, 2010, 2013). 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 (European Commission, 2011). Both the NM and ANSPs are therefore expected to meet the imposed SES Performance Scheme ATFM delay targets. In 2014, for instance, the direct NM contribution was almost one million minutes of ATFM en-route delay savings (0.09 min per flight on average), out of which 150,000 min of delay reduction was achieved via more direct routings (EUROCONTROL, 2015a). Both the NM and ANSPs involve significant resources to explore a range of potential ATFM measures to utilize available capacity, before considering to regulate the demand (EUROCONTROL NMOC, 2016). This sometimes leads to implementation of so called scenarios[3] by ANSPs, usually through re-routings of flights, to avoid excessive ATFM delays (EUROCONTROL NMOC, 2016). The number of such scenarios more than doubled since the beginning of the SES Performance Scheme implementation: 2076, 3371 and 5226,[4] in 2012, 2013 and 2014 respectively.

AOs 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 (EUROCONTROL, 2015b). 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 (Van Der Veldt, 2015). One could argue that the latter delay is primary concern for AOs business, while the former is binding for capacity providers, resulting in divorced delay phenomenon perspectives.

Understanding that ATFM delay savings is one of the drivers in capacity providers decision making process, we first estimate the effects of the current policy and practice which minimizes ATFM delay of regulated flights (the NM perspective) on propagated delays (AO perspective). This will serve as a benchmark against our approach and proposed model which rather focuses on minimizing delay propagation.

2.2. Airport slot adherence

Although there are no airport-related SES performance targets at the network level presently, a number of services and solutions for better airport-ATM integration and exploitation of airport capacity are envisaged with the SES initiative (SESAR Consortium, 2012). In the context of our paper, particularly relevant is EUROCONTROL Centralised Service 1 (CS1): Flight Plan and Airport Slot Consistency Service (FAS) (EUROCONTROL, 2014a). The aim of CS1-FAS is to check the consistency of flight plans against airport slots on a centralised basis; this will result in better exploitation of airport capacity and

[3] Scenarios are ATFM solutions to capacity bottlenecks or specific operational needs of an ANSP aiming at offloading congested areas by re-routing of flights or limiting the highest flight level that can be planned for a flight (EUROCONTROL NMOC, 2016).

[4] Data is available through EUROCONTROL Demand Data Repository (DDR): http://www.eurocontrol.int/ddr service or through EUROCONTROL ATFCM statistics service at the OneSky Online Extranet EUROCONTROL portal https://ext.eurocontrol.int/. Both services serve as data sources for this study; we refer to them as DDR and ATFCM Service further in the text.

improved flight punctuality, helping to enhance predictability and consistency (EUROCONTROL, 2014a). Currently, (strategic) planning and (tactical) operations with respect to agreed and allocated airport capacity is not linked, respectively not taken into account during tactical operations (EUROCONTROL, 2014a). Adamson (2015) presents significant benefits for AOs at small Greek airports upon introducing airport slot monitoring coupled with ATFM measures which were taking correct airport slots into account. CS1-FAS envisage sending warnings to AOs, and even rejection of FPLs, in case of airport slot non-adherence; we complement the concept by proposing an approach to increase airport slot adherence in cases when arriving and/or departing flights are affected by regulation, i.e. ATFM delay.

2.3. Previous theoretical contributions and a way forward

A comprehensive review of mathematical modelling and various formulations of demand-capacity imbalance problem is presented in Agustín et al. (2010) and a more recent summary of trends and opportunities in the area of demand and capacity management is given in Barnhart et al. (2012). We briefly reflect on selected previous contributions.

Primary focus of our research is to demonstrate applicability of proposed methodology using real-world examples of demand-capacity imbalance problem in Europe: the case when a single capacity resource is constrained, taking into account network as a whole. Tošić et al. (1997) propose a binary integer programming model to solve an en-route sector capacity shortfall, by minimizing cost of ground delays and re-routings. Ground delays are generally perceived safer and less costly solution compared to holding aircraft in the air (Liu and Hansen, 2013) while re-routings are observed as a mean of reducing ground delays (and associated costs thereof) by utilizing neighbouring uncongested en-route sectors (Jovanović et al., 2014). Castelli et al. (2011) propose a market-based ATFM slot allocation to minimize the overall cost of delay, and demonstrate cost benefits of such approach using a real-world case where all the flights are subject to a single regulation and CASA slot allocation as a benchmark. Likewise, our model builds on CASA, with the difference that we stay in 'delay domain', i.e. we minimize propagated delay rather than delay cost *per se*. The reason for this is practical, as it is easier to follow the logic behind the model and directly compare the results against the current policy (Andreatta et al., 1997), as we use the same delay metrics. Flow manager decides using time as a criterion (Leal de Matos and Powell, 2003), as the AOs are reluctant to reveal, or even not in a perfect position to calculate, delay cost for each flight (Castelli et al., 2011); the future User Driven Prioritisation Process (UDPP) concept will offer a possibility to AOs to indicate a priority order of flights affected by delays (SESAR Consortium, 2012). Nevertheless, we estimate the delay costs of proposed solutions using individual cost functions, as we are able to differentiate between strategic cost of schedule buffer and tactical cost of delay for each flight (Cook and Tanner, 2015).

Vranas et al. (1994) used ground slack time to limit coupling of consecutive flights, 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 (homogenous demand), unrealistic, but well-established practice of Federal Aviation Administration in the US. A number of papers also focus on large-scale instances of the network and computational times (Bertsimas and Patterson, 1998; Bertsimas et al., 2008; Churchill et al., 2009; Agustin et al., 2012) applying a combination of various DM actions (ground delays, re-routings, speed control and flight cancellation) to minimize aggregated delay (cost). A central ATM decision maker decides on a set of DM actions to satisfy capacity and coupling constraints, assuming that aircraft rotations and turnaround times are known in advance. Churchill et al. (2009) notice that there is a limitation for using the coupling of consecutive flights in practical model applications, not because of increasing computational times, but due to the fact that the information of aircraft rotations is proprietary and airlines are not likely to disclose them. In our approach, we share the perspective of the NM in Europe: the schedule information is available for one leg of an aircraft rotation and there is no link available to the subsequent leg. Alternatively, we explicitly distinguish between strategic and tactical schedules and use ATFM delay as an instrument to reduce delay propagation. Furthermore, we observe demand as heterogeneous recognizing the different scheduling practices among AOs.

The concept of in-house utilisation and reallocation of flights' schedule buffers to reduce delay propagation has already been shown as potentially beneficial to AOs (AhmadBeygi et al., 2008). In our research we adapt and apply the methodology at a network (central) level; on a related note, de Villemeur et al. (2011) analyse (cost-benefit) the effects of central planning of schedule buffers, instead of the current market based. As a digression, once airborne, flight could complementary compensate some departure delay, be it in terms of minutes or cost savings. For instance, Cook et al. (2009) suggest using dynamic cost index (speed *vs.* fuel burn *vs.* environment trade-off) concluding that, in certain cases, even small delay recoveries can be worth the fuel penalty in terms of increasing arrival predictability and minimizing disruption at the airport (see also Delgado and Prats, 2012). We expect a similar trade-off to arise between equity and efficiency following the application of our concept, having in mind that the current FCFS policy is shown to be equitable in terms of ATFM delay minutes distribution (but not necessarily in the cost domain, see Castelli et al., 2011). This seems to be a widely observed phenomenon; for instance, Lulli and Odoni (2007) propose a deterministic model for ATFM problem specific for European ATM and notice the same, therein defined, equity *vs.* efficiency conflict. A number of papers address equitable resource allocation in the ATM, defining equity as "equal outcome" (Transportation Research Board, 2011), considering equity over a period of time (Tošić et al., 1995) or as "delayers pay principle" (Levinson and Rafferty, 2004). A few studies also consider balancing between efficiency and equity, for instance, by including both components in the objective function (Glover and Ball, 2013) or bi-level approach maximizing efficiency first and equity second (Kuhn, 2013). We do not address the equity issue *per se* in our model, however, we discuss the consequences of the operational principles applied therein (Section 5). Namely, it would be interesting to see to which extent would different AOs favor this kind of policy, since the net outcome (effect) of the trade-off involved is not straightforwardly clear, especially given the heterogeneous landscape of AOs' business models in Europe. In the end, equity might also be seen as largely a matter of perception and metrics used to measure it (Glover and Ball, 2013), so we compare both delay minutes and estimated cost distribution outcome of the model, being aware that it's not necessarily those metrics that AOs find most relevant in this regard. Notably, neither equity, nor terms with similar notions, are explicitly addressed in the current EC high-level transport policy (Jovanović et al., 2015).

Lastly, we address the practical issue of adherence to airport slots, in case of disturbance of operations due to en-route sector regulation. A major focus of research regarding airport slots is on airport slot trading (e.g. Pellegrini et al., 2012) and effects thereof (e.g. Fukui, 2014), slot allocation mechanism (among many, Avenali et al., 2015; Corolli et al., 2014) and efficiency thereof (Madas and Zografos, 2008; Ranieri et al., 2013). Castelli et al. (2012) propose an airport slot allocation (deterministic) model, considering the network constraints and matching the departing and arriving slot, in a more equitable manner. Etxebarria et al. (2013) simulate different prioritization strategies at a network level, one of them being priority for flights flying to congested airports, but found no benefits compared to FCFS policy. Our focus is on protecting the scarce capacity resources when some of the flights operating from slot coordinated airports are delayed due to an ATFM en-route regulation. This approach is also very well aligned with the new SESAR (SES ATM Research) concept 'Short-Term Air Traffic Flow and Capacity Management Measures' (STAM)[5] (EUROCONTROL, 2014b).

3. Minimizing delay propagation and improving airport slot adherence: two-level optimization model

3.1. Rationale

CODA all-cause delay analysis shows that, after recovering overnight, reactionary delay starts accumulating in the morning and continuously builds up during the day (EUROCONTROL CODA, 2015). AhmadBeygi et al. (2008) show that flights delayed in the morning will propagate more delay, suggesting that a flight disrupted early in the day will benefit more substantially from increased buffer (to absorb disruption) than will a flight disrupted later in the day. This also supports a conventional wisdom that airlines pay more attention to flights' punctuality in the morning, but focus on transfer passengers in the evening (Jetzki, 2009); partially due to the high (non-linear) cost of tactical delay, for instance, due to missed passenger transfers and long delay compensations (Cook and Tanner, 2015). On the other hand, adding schedule buffers increases resilience to delay propagation, consequently increasing airlines' strategic costs (in a linear fashion). Therefore, AOs are able to balance between the buffer levels and anticipated tactical delay (Cook and Tanner, 2015). Cook and Tanner (2015) further argue that strategic costs and tactical costs are not independent, due to costs of reactionary delays: for instance, if no buffers were used to absorb a portion of delay, the reactionary costs would increase markedly and the tactical costs would be significantly higher. A minute of strategic cost of delay is approximately three times lower than a minute of its tactical counterpart, with a historical trend of lowering strategic and increasing tactical unit delay costs (Cook and Tanner, 2015). With this in mind, our approach which tends to distribute ATFM delay minutes over the (long) schedule buffers sounds reasonable in the cost domain too, on a system (network) level.

Assuming that majority of early rotations still have schedule buffers at large (de Villemeur et al., 2011), we test the proposed methodology for morning regulations. Note that, as the total delay inevitably 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 evening operations, perhaps passenger-centric methodology for delay assignment (Montlaur and Delgado, 2015) would better answer AOs needs.

AOs attach great value to their flight planning flexibility and tend to decide on their route and flying times at a rather short notice; they are obliged to submit a FPL at latest 3 h before the estimated off block time (EOBT), see Fig. 1. This means that even though coordinated airports strategically balance demand and capacity through airport slots, AOs could still tactically file their EOBT much earlier (or later in case of delay) than strategically planned time of departure (STD). CODA reports that almost 20% of flights depart 5 or more minutes before STD, 40% arrive 5 or more minutes before scheduled time of arrival (STA), with 10% of flights arriving 15 min in advance (EUROCONTROL CODA, 2015). Flexibility to tactically shift desired take-off time much earlier than strategically planned, thus increasing strategically allocated buffer, could also cause congestion problems at airports already operating at their capacities (EUROCONTROL CODA, 2015). Therefore, in the ATFM slot allocation process, we aim to control ATFM delay distribution in a way so as to bring flights operating from/to slot coordinated airports closer to their strategic time of operations, i.e. to airport slots.

3.2. Problem statement and model assumptions

We define the demand-capacity imbalance problem as follows: for an en-route sector regulation, defined by duration and declared rate, assign regulated flights to ATFM slots to minimize delay propagated to subsequent flights and maximize airport slot adherence, such that each flight is assigned only one ATFM slot and one ATFM slot is assigned to one flight only.

[5] Basically, STAM are minor spatio-temporal flight profile modifications applied to a few selected flights to reduce complexity of anticipated traffic loads (EUROCONTROL, 2014b).

A regulation is defined by the geographical reference (location), activation, start (r_{start}) and end (r_{end}) time and with the rate of aircraft allowed to enter a regulated location in an hour (C_r). A flight can be assigned to any ATFM slot which ends after the flight's estimated time over (ETO) the regulated location. The number of ATFM slots is calculated as (1):

$$N = C_r(r_{end} - r_{start}). \tag{1}$$

ATFM slots $i \in \{1,\dots,N\}$ are defined by their start time L_i (2), (3) where

$$L_1 = r_{start}; \quad L_i = L_{i-1} + 1/C_r, \quad \forall i \in \{2,\dots,N+1\} \tag{2}$$

$$[L_i, L_{i+1}], \quad \forall i \in \{1,\dots,N\}. \tag{3}$$

Demand is known *a priori*: the NM has the tactical schedules based on FPLs and we assume that it also has strategic schedules. The difference between strategic and tactical schedules for a flight represents strategic buffer (b_s). The definition is in line with methodology used in Jetzki (2009) to estimate strategic schedule buffers per different market segment in Europe. We denote with b_t tactical buffer for a flight *f*; it represents the flexibility for AOs to shift EOBT before STD (early flight, $b_t > 0$), thus increasing strategic schedule buffer, or after STD (delayed flight, $b_t < 0$), decreasing strategic schedule buffer. Finally, we define schedule buffer b_f for a flight *f* as a sum of strategic and tactical buffer (4):

$$b_f = (STA_f - STD_f) - (ETA_f - EOBT_f) + b_t. \tag{4}$$

Note that when strategic and tactical departure times (STD, EOBT respectively) are aligned, buffer is the difference between scheduled and estimated time of arrival at gate (STA, ETA respectively), Fig. 1.

ATFM delay d^A_{fi} and propagated delay d^P_{fi} for each flight *f* and slot *i* are calculated, respectively by (5) and (6):

$$d^A_{fi} = (L_i - ETO_f)^+, \tag{5}$$

$$d^P_{fi} = (d^A_{fi} - b_f)^+, \tag{6}$$

where

$$(x)^+ = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases}. \tag{7}$$

If a delayed flight *f* still arrives earlier than scheduled, we assume that no delay is propagated to the next flight, therefore d^p_f is set to zero; otherwise, the delay not absorbed by buffer propagates to the subsequent flight. In practice, 1 min of primary delay generated on average 0.8 min of reactionary delay in 2014 (EUROCONTROL CODA, 2015); with some variation, this has been a relatively stable ratio over the years (Cook and Tanner, 2015). We simulate, *ex post*, the actual effects of ATFM delayed flights on the subsequent rotation, taking into account potential delay recovery during the turnaround phase.

We assume that strategic schedules and airport slots are aligned (see Fig. 1). Airport slot adherence is defined as the absolute (time) difference between strategic and tactical (ATFM delayed) schedules, separately for departures from and arrivals at coordinated airports (Eqs. (19), (20)). The realization of flights is assumed as planned. We test the effects on results of violation of this assumption, i.e. when regulated flights do not depart on time.

3.3. Model

In this section, we propose a two-level mixed-integer programming model to minimize propagated delay and subsequently maximize airport slot adherence. We optimize in two steps because our priority is to minimize propagated delay; slot adherence is only to be improved without increasing overall delay. We focus on a set of regulated flights, observed in the network composed of airports and sectors with limited capacity, as well as capacity restrictions of a set of regulated en-route sectors. We use binary matrices to map from an elementary discrete time grid to higher level discrete time grids, corresponding to airport slots, sector slots or regulation slots. A generic mapping matrix is defined as $B \in \{0,1\}^{I \times T}$ where *I* is the number of aggregated slot intervals and *T* is the total number of periods in the elementary time horizon considered. B_{it} is equal to 1 if period *t* is in time slot interval *i*; 0 otherwise.

3.3.1. Level 1 – minimizing propagated delay

Given the network under consideration, we propose an optimization model to find per-flight delay (ATFM slot) assignment which minimizes the overall propagated delay, subject to capacity constraints; we refer to this model as MINP. Note that other non-regulated and regulated (i.e. subject to a regulation other than the considered one) flights sharing the same network under consideration may affect capacity, but these flights are assumed to be fixed and their impact on capacity is incorporated in the input parameters (capacities decremented accordingly). The MINP model uses notation as defined in Table 1:

Table 1
Sets and indices.

Sets and indices	
F	Set of flights, indexed by f
A	Set of coordinated airports, indexed by a
S	Set of sectors, indexed by s
R	Set of regulations, indexed by r
S^R	Set of regulated sectors, indexed by s_r
$F_a^{dep}, F_a^{arr}, F_s$	Subset of flights departing from airport a, arriving at airport a and using sector s
Parameters	
$\vec{c}_a^{dep}$	Capacity vector of departure slots at airport a
$\vec{c}_a^{arr}$	Capacity vector of arrival slots at airport a
$\vec{c}_s^{sec}$	Capacity vector of entry slots at sector s
b_f	Schedule buffer of flight f
$\vec{e}_{fl}^{dep}$	Unit vector $\in \{0,1\}^T$ with 1 in $(t_f^{dep}+l)^{th}$ position, where t_f^{dep} is the expected departure time period according to schedule (EOBT)
$\vec{e}_{fl}^{arr}$	Unit vector $\in \{0,1\}^T$ with 1 in $(t_f^{arr}+l)^{th}$ position, where t_f^{arr} is the expected arrival time period according to schedule (ETA)
$\vec{e}_{fls}^{sec}$	Unit vector $\in \{0,1\}^T$ with 1 in $(t_f^{sec}+l)^{th}$ position, where t_f^{sec} is the expected entry time of flight f into sector s according to schedule (ETO)
B_a^{dep}, B_a^{arr}	Binary matrix mapping elementary time horizon into the aggregated departure and arrival time grids at airport a
B_s^{sec}	Binary matrix mapping from the elementary time horizon into the aggregated slots used to count entries at sector s
$B_{s_r}^{reg}$	Binary matrix mapping from the elementary time horizon into the aggregated slots used by regulation r on sector s_r
Decision variables	
u_{fl}	Binary variable indicating whether flight f will be delayed by $l \in \{0,1,\ldots,l_{max}\}$ time units (with l_{max} representing the maximum delay that can be assigned to a flight)
d_f^p	Propagated delay for flight f

(MINP):

$$\min \sum_{f\in F} d_f^p \tag{8}$$

$$s.t. \sum_{f\in F_a^{dep}} B_a^{dep}\left(\sum_{l=0}^{l_{max}} u_{fl}\vec{e}_{fl}^{dep}\right) \leqslant \vec{c}_a^{dep} \quad \forall a\in A \tag{9}$$

$$\sum_{f\in F_s} B_s^{sec}\left(\sum_{l=0}^{l_{max}} u_{fl}\vec{e}_{fls}^{sec}\right) \leqslant \vec{c}_s^{sec} \quad \forall s\in S \tag{10}$$

$$\sum_{f\in F_{s_r}} B_{s_r}^{reg}\left(\sum_{l=0}^{l_{max}} u_{fl}\vec{e}_{fls_r}^{sec}\right) \leqslant \vec{1} \quad \forall r\in R \tag{11}$$

$$\sum_{f\in F_a^{arr}} B_a^{arr}\left(\sum_{l=0}^{l_{max}} u_{fl}\vec{e}_{fl}^{arr}\right) \leqslant \vec{c}_a^{arr} \quad \forall a\in A \tag{12}$$

$$d_f^p \geqslant \left(\sum_{l=0}^{l_{max}} l u_{fl} - b_f\right) \quad \forall f\in F \tag{13}$$

$$d_f^p \geqslant 0 \quad \forall f\in F \tag{14}$$

$$\sum_{l=0}^{l_{max}} u_{fl} = 1 \quad \forall f\in F \tag{15}$$

$$u_{fl}\in\{0,1\} \quad \forall f\in F, l\in\{0,1,\ldots,l_{max}\}. \tag{16}$$

MINP assigns ATFM delays to flights to minimize the sum of propagated delays (8). Inequalities (9)–(12) are the capacity constraints for departure airports, sectors, regulated sectors and arrival airports, respectively. Constraints (13) define the propagated delay of flight f as its ATFM delay minus its buffer. Constraints (14) are the non-negativity requirement for propagated delay variables. Equations (15) state that at most one delay can be assigned to each flight. Finally, constraints (16) are the binary restrictions for variables u_{fl}.

3.3.2. Level 2 - Optimizing airport slot adherence

At the second level, we seek an ATFM slot allocation, i.e. ATFM delay distribution, to improve airport slot adherence; this model is referred to as APSA.

The model uses following additional notation:

- F^{co} : set of flights departing from or arriving at a coordinated airport
- STA_f : scheduled time of arrival for flight f
- STD_f : scheduled time of departure for flight f

- d_f^{opt} : optimal propagated delay for flight f, obtained by solving MINP model
- h_f^{dep} : variable representing airport slot adherence at departure for flight f
- h_f^{arr} : variable representing airport slot adherence at arrival for flight f

(APSA):

$$\min \sum_{f \in F^{co}} h_f^{dep} + \sum_{f \in F^{co}} h_f^{arr} \tag{17}$$

s.t.(9)–(16)

$$\sum_{f \in F} d_f^p = \sum_{f \in F} d_f^{opt} \tag{18}$$

$$h_f^{dep} = \left| STD_f - t_f^{dep} - \sum_{l=0}^{l_{max}} lu_{fl} \right| \quad \forall f \in F^{co} \tag{19}$$

$$h_f^{arr} = \left| STA_f - t_f^{arr} - \sum_{l=0}^{l_{max}} lu_{fl} \right| \quad \forall f \in F^{co}. \tag{20}$$

APSA model aims at finding new delay assignments which maximize airport slots adherence (17) without increasing global propagated delay (18). Finally, Eqs. (19) and (20) define airport slot adherence at departure and arrival, respectively. It should be noted that (19) and (20) can be elegantly linearized; we omitted this step for the sake of clearer position.

4. Case study

4.1. Experimental design and data

The main data source used is EUROCONTROL Demand Data Repository (DDR) Service, which provides historical demand and capacity data, accessed through EUROCONTROL's Network Strategic Tool (NEST) software (EUROCONTROL, 2016), used for data processing (see also Jovanović et al., 2014). We use two different morning en-route regulations for model testing and comparison, Table 2. To get a sense of scope of the instances, we consider 23 airports and 104 sectors for Regulation 1 and 61 airports and 232 sectors for Regulation 2, with several hundred of other regulated and non-regulated flights in both instances. All the regulated flights were subject to one regulation only, so the FCFS policy should give minimum ATFM delay. However, CASA is inherently dynamic and coupled with complex rules for exemption or inclusion[6] of flights into a regulation, so the resulting ATFM delay (Table 2) distribution is not necessarily a reproduction of the strict FCFS rule (EUROCONTROL NMOC, 2016). Therefore, we simulate CASA algorithm to obtain FCFS compatible ATFM delay and ATFM slot allocation (last column, Table 2) (EUROCONTROL, 2016).

Further, CASA does not take into account wider network constraints, other than those of regulated sector(s) (EUROCONTROL NMOC, 2016), so CASA solution may violate hard capacity constraints envisaged in our model. To provide a reasonable result comparison between CASA and our model, we design experiments to include two distinct cases:

1. Infinite network capacity. This is the default CASA setting; we neglect the network capacity constraints to obtain results with MINP and APSA (we refer to this case as MINP_{inf} and $\text{APSA}_{\text{inf,}}$ respectively).
2. Limited network capacity. The limited network capacity (airports and sectors) is accounted for. To simulate CASA with such constraints, we use our model to minimize ATFM delay by substituting propagated delay with ATFM delay in the objective function (8). We refer to this model as MATFM, the results of which are now directly comparable to MINP and APSA.

With NEST, we are able to capture the dynamics of the airspace network, e.g. sector opening or closing, and consequent capacity changes (EUROCONTROL, 2016). We use flights' sector entry and crossing times for each regulated flight, as well as for other regulated and non-regulated flights, to estimate loadings of sectors and airports of the (dynamic) network considered. For sector loads, we use hourly entry counts, i.e. number of flights entering a sector during an hour, as the usual practice, and equivalent 20 min entry counts for slot coordinated airports.

We use detailed flight trajectories and tactical departure and arrival times of regulated flights, based on latest valid FPL. We define three schedule buffer distributions to reproduce aggregated high level statistics per different market segment[7] in

[6] For instance, flights flying from outside the NM/ATFM area of service are not subject to regulation (EUROCONTROL NMOC, 2016); we exempt these flights from our analysis as well (one flight per regulation, so the final traffic samples are 23 and 62, respectively).

[7] We categorize AOs based on AO code, airport pair and aircraft model to, as closely as possible, replicate the methodology in Jetzki (2009); if a flight's segment is not conclusive, we assign the market segment with narrower buffer distribution. For a few non-scheduled (operating by unpublished schedules) flights in the larger traffic sample, we assume P2P buffer distribution.

Table 2
Regulation details. source EUROCONTROL DDR.

Reg. No.	Reg. ID	Reference location	Reg. start	Reg. end	Rate	Nb. of flights	ATFM Delay (reported)	ATFM Delay (simulated)
1	FTE321E	LFFFTE	21/11/2014 07:00	21/11/2014 08:00	25	24	243 min	208 min
2	LEP1U106	LECBP1U	06/10/2014 08:20	06/10/2014 10:20	41	63	334 min	295 min

Jetzki (2009): on average, Low Cost (LCC) have 5 min buffer time, Hub&Spoke (H&S) 3 min and 2 min buffer for Point to Point (P2P) operations. Jetzki (2009) estimates that between 20% and 30% of all flights have their actual gate-to-gate times longer than published schedules (see Mayer and Sinai, 2003), which seems to be in line with the current state (EUROCONTROL CODA, 2015). We propose uniform schedule buffer distribution per market segment:

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

To test the models for each regulation and traffic mix, we run 30 iterations with different buffer samples, drawn from the distributions defined.

To evaluate solutions of different models, we estimate delay cost per flight as a sum of strategic and tactical delay cost, using (Cook and Tanner, 2015):

- Linear function for the (sunk) cost of strategic delay – c_f^s, where $c_f^s = \alpha^s \cdot b_s$;
- Non-linear function for the cost of tactical delay (beyond strategic) – c_f^t, including reactionary delay cost estimates, where

  Bullet
  $c_f^t = \alpha^t \cdot (d_f^A - b_f)^2 + \beta^t \cdot (d_f^A - b_f) + \gamma^t$, if $d_f^A - b_f > 0$ or
  Bullet
  $c_f^t = 0$, if $d_f^A - b_f \leqslant 0$, i.e. if ATFM delay is absorbed by buffer.

We rely on detailed at-gate delay costs tabulated in Cook and Tanner (2015) to estimate parameters α^s, α^t, β^t and γ^t per aircraft type, or linearly adjusted costs based on aircraft weight if an aircraft type is not tabulated (see more in Cook and Tanner, 2015). While it is clear that a flight with positive buffer time already has a starting cost of strategic delay, the same cannot be stated for a flight with negative schedule buffer. Namely, the reason for the (presently) observed negative buffer is not known, e.g. is it the AO's policy or an individual case due to operational limitation and inability to take a shorter route, hence, it is rather difficult to assign appropriate (starting) cost. Although Cook and Tanner (2015) indicate that such flight would have markedly increased cost of delay, we observe it as a flight with zero strategic cost and 'nominal' tactical cost; otherwise, we expect that our model would be favoured in comparison with CASA.

For ex post analysis, we first test the effect on results when regulated flights do not depart in line with calculated off block time (COBT; EOBT adjusted for ATFM delay, Fig. 1). In October and November 2014, 90% of regulated flights departed within ATFM slot tolerance window (STW) of [−5 min, +10 min], meaning that vast majority of regulated flight departed within 15 min of calculated take off time (CTOT).[8] To have a wider dispersion, we assume that all the regulated flights depart within this time window with uniform distribution $U[-5\text{ min}, 10\text{ min}]$ and run 1800 iterations (30 schedule buffer distributions for both regulations and 30 different samples of ATFM slot adherence minutes).

We also test how much of delay actually propagates to subsequent flights, knowing that some of the inbound delay could be absorbed in the turnaround phase. Jetzki (2009) uses several indicators for such estimation and we adopt two:

- Schedule padding-ground (SPG), which measures the difference between departing and inbound (primary) delay. This measure reveals if a flight could recover some delay from delayed inbound flight on the ground.
- Absorbed inbound delay (AID), which measures the difference between actually reported AO reactionary departure delay of the subsequent flight and inbound (primary) delay of preceding flight. This indicator exactly shows how much of inbound delay actually propagates to the following flight and is reported as reactionary delay by AOs.

SPG indicator shows that H&S and P2P could recover one minute of delay on the ground on average, while LCC actually adds more delay during the turnaround phase, albeit from somewhat higher inbound delay (Jetzki, 2009). To reproduce the

[8] Based on data analysis (source DDR). This statistics is also available in the NM Monthly Adherence to ATFCM Slots reports provided by EUROCONTROL's ATFCM service.

aggregate statistics therein, we assume that H&S and P2P could recover between 4 min or add up to 2 min of new delay (uniformly in between), and that LCC in best case do not add any new delay and add up to 5 min of new turnaround delay (also uniformly in between). AID reveals that H&S and P2P could absorb on average 8 min of inbound delay, while LCC report around 5 min on average (Jetzki, 2009). For AID, we assume U[5 min,11 min] for H&S and P2P, and U[2 min,7 min] for LCC. Note that Jetzki (2009) estimates SPG and AID for the flights which are delayed on arrival. Since we estimate the impact of ATM system on reactionary delay, we also don't consider regulated flights with zero ATFM delay (regulated but not actually delayed) or delayed flights still arriving before STA.

4.2. Results

Without any loss of generality, we assume that EOBT coincides with STD. A sample of schedule buffers is drawn from the buffer distributions and added to tactical flight time (if a flight has negative schedule buffer, STA will be before ETA). We draw 30 different samples and run simulations using 4 different models for the two regulations; the results are summarized in Table 3.

Almost the same results for ATFM delay for CASA (208 min) and MATFM (209 min) for Regulation 1 indicates that the network capacity represent only a negligible constraint in this case. The same stands for both MINP models, which give slightly higher ATFM delay (212 min) and lower propagated delay (129 min) compared to CASA (143 min) and MATFM (155 min). While the difference between tactical and strategic schedules is lower (airport slot adherence is higher) for both $MINP_{inf}$ and MINP compared to CASA and MATFM, APSA could not further improve the results already obtained in the first optimization. In case of Regulation 2, on the other hand, the difference between CASA (295 min) and MATFM (354 min) ATFM delay indicates that some (unregulated) en-route sectors and/or airports have higher demand than declared capacity. This is an operationally well-known phenomenon called 'overdeliveries',[9] which we discuss further. $MINP_{inf}$ ATFM slot allocation produces 146 min of propagated delay, while CASA allocation results with 198 min of delay propagation. The equivalent constrained models yield total delay propagation of 261 min for MATFM and 197 min for MINP. Unlike in Regulation 1, airport slot adherence was improved by APSA for both $MINP_{inf}$ and MINP, albeit in different ways. Namely, the improvement for $MINP_{inf}$ comes at the expense of higher ATFM delay, i.e. airport slot adherence improvement equals the increase in ATFM delay. On the other hand, in MINP case APSA improves airport slot adherence for 8 min and increases ATFM delay for only 1 min.

Turning to the cost domain,[10] the average cost of delay (strategic and tactical) for Regulation 1 for $MINP_{inf}$ is 4011EUR and for CASA 3927EUR. The results indicate that ATFM delays are such that could not be absorbed by (large) schedule buffers, so the dominant cost driver is non-linear tactical delay (65% of total delay costs in both cases). Since we use tactical costs with estimated reactionary cost for the level of tactical delay, and not the actual reactionary delay cost (not separately provided in Cook and Tanner, 2015), these results should be taken with a dose of reservation. On the other hand, the average delay cost for MATFM was initially much higher at 5282EUR (with 74% tactical cost), while the cost of MINP is the same as in unconstrained equivalent. These results should also be observed in the light that a different (optimal) delay assignment in MATFM make possible to reduce the delay costs (since CASA and MATFM globally produce the same ATFM delay figures). After assessing a couple of different ATFM slot allocations for MATFM, keeping the optimal ATFM delay, we found a solution with associated cost of 3914EUR, a value reported in Table 3 (note that such second-level cost minimization was not in the scope of this research).

The Regulation 2 average delay costs are 2761EUR for CASA and 2109EUR for $MINP_{inf}$. Although this regulation is twice as long and has almost three times more traffic, the overall delay cost is lower (as well as the average ATFM delay). First, this means that there are a lot of available ATFM slots (82 ATFM slots and 62 regulated flights, compared to 25 ATFM slots and 24 regulated flights in Regulation 1) to re-allocate flights. Second, traffic mix is different and there are proportionally more LCC flights with somewhat higher (on average) schedule buffers. The cost shares are the opposite in this case and somewhat different: for CASA 40% of total cost are tactical, but only 20% for $MINP_{inf}$. For capacity constrained models, MINP gives total cost of 3476EUR and MATFM initially 4086EUR; after repeating the same second stage cost reduction, we lowered the MATFM cost to 3506EUR without increasing ATFM delay. The share of tactical and strategic costs is almost the same: 52% of tactical cost for MINP and 59% of the same for MATFM, as a consequence of higher ATFM delay compared to unconstrained case.

We further compare the delay costs after improving airport slot adherence and we run APSA for $MINP_{inf}$ and MINP for both regulations. ATFM slot re-allocation for Regulation 1 to find an optimal airport slot adherence improved the delay cost to 3845EUR, compared to $MINP_{inf}$ only. For the capacity constrained case the delay cost also decreased for MINP to 3974EUR. Notably, although there was no improvement in airport slot adherence in terms of minutes on average, average costs was lower in both cases. Contrary, for Regulation 2, improving airport slot adherence comes with higher delay cost for $MINP_{inf}$ (2483EUR), while in capacity constrained cases, MINP delay cost slightly decreased (3459EUR).

[9] Reader is referred to: http://www.skybrary.aero/index.php/Sector_Over-deliveries_and_Overloads and http://www.skybrary.aero/index.php/Sector_Over-Deliveries_Due_to_Non-Adherence.

[10] To illustrate the cost calculation in this study: for 10 min schedule buffer and 15 min of ATFM delay, at gate total delay costs for Airbus A319 and Boeing 777-200 are 203EUR and 467EUR, respectively. Note that strategic buffer minutes are calculated as delay cost, even if flight is not ATFM delayed by regulation, since the cost has already 'occurred' at strategic level.

Table 3
Average (rounded) propagated (d^p) and ATFM (l_{ATFM}) delay, airport slot adherence ($h^{dep} + h^{arr}$) minutes and delay costs (EUR).

		Regulation 1							Regulation 2						
	Metrics	Delay (min)			Adher. (min)		Delay cost (EUR)		Delay			Adher. (min)		Delay cost (EUR)	
	Model	d^p	l_{ATFM}		$h^{dep}+h^{arr}$				d^p	l_{ATFM}		$h^{dep}+h^{arr}$			
Infinite capacity	CASA	143	208		164		3972		198	295		340		2761	
	MINP(APSA)$_{inf}$	129	MINP	APSA	MINP	APSA	MINP	APSA	146	MINP	APSA	MINP	APSA	MINP	APSA
			212	212	132	132	4011	3845		312	316	218	214	2109	2483
Limited capacity	MATFM	155	209		138		3914		261	354		300		3506	
	MINP(APSA)	129	MINP	APSA	MINP	APSA	MINP	APSA	197	MINP	APSA	MINP	APSA	MINP	APSA
			212	212	133	133	4011	3974		380	381	259	251	3476	3459

4.3. Ex-post analysis

Due to generously wide ATFM slot tolerance window of 15 min and assumed uniform distribution over the period, propagated delay increased markedly in vast majority of iterations for Regulation 1, Table 4 (note that, based on assumed STW distribution, regulated flights depart 2.5 min late on average). Nevertheless, even in case when delayed flights do not depart as planned still both MINP and $MINP_{inf}$ propagate less delay d^p(STW) than CASA and MATFM. SPG captures the difference between inbound delay of previous flight and departure delay of the following flight. Due to predominant H&S in the sample for Regulation 1, in majority of the cases some of inbound delay was absorbed during the turnaround process. Still, total departure delay of the subsequent flights is lower for both MINP models, compared to CASA and MATFM. The same stands for AID, with the difference that gap between $MINP_{inf}$, MINP and CASA becomes negligible, meaning that AOs would report the same actual reactionary delay.

Results of the second regulation reveal different situation. The ratio d^p(STW)/d^p for MINP and $MINP_{inf}$ for Regulation 2 is around 1.8 and 2.1 respectively, meaning that due to ATFM slot non-adherence regulated flights could actually propagate twice as much delay. The same ratio in all other cases fluctuates around 1.5. This shows that for the Regulation 2 most of the ATFM delay was already absorbed by (larger on average) schedule buffers and that failing to comply with ATFM slot could more than proportionally increase delay propagation. However, total propagated delay minutes still favor $MINP_{inf}$ and MINP over CASA and MATFM. SPG indicator also shows difference compared with the first case – total departure delay of subsequent rotations is increased, due to predominant presence of LCC in the sample (LCC adds more delay in the turnaround phase). In line with SPG, AID is also proportionally higher compared to Regulation 1.

Ex post analysis of delay propagation for APSA model reveal very similar results.

Although we were able to improve airport slot adherence with our model for both regulations, assuming on-time operations and deterministic flight times, all the ex post tests showed high sensitivity to violation of the assumptions. Not surprisingly, wide ATFM slot tolerance window in most of the cases cancels out better performance of our models for both regulations. Finally, it is not just lowering the adherence to airport slots, but failing to depart on time also led to over-delivery cases in several sectors and demand was up to 10% higher than the declared sector capacity (assuming compliance with FPL for all the other non-regulated and regulated flights in the network).

5. Discussion

Statistical test show that average delay propagated to subsequent flights is significantly lower for MINP models, compared to ATFM minimization model counterparts ($\alpha = 0{,}05$ for all the tests). The same stands and for ex post tests, expect for the difference between average propagated delay in cases when departure times vary d^p(STW) and reported reactionary delay d^p(AID) between MINPinf and CASA for Regulation 1. While ATFM delay for Regulation 2 is significantly higher for MINP models, it is not the case in Regulation 1. On the other hand, the only statistically significant difference in improving airport slot adherence is for Regulation 2, in case of limited network capacity.

While in the delay duration domain MINP results surpass the CASA equivalent, the picture is not as clear with delay costs and some results require further discussion. For Regulation 1, delay costs are generally lower for CASA models. Interestingly, APSA optimization to improve airport slot adherence minutes actually improved average delay cost, but not adherence minutes. For Regulation 2, MINP models have lower total delay cost compared to CASA models. Again, perhaps somewhat counter-intuitively, improvement of airport slot adherence for MINP gives higher ATFM delay, but lower delay cost. Also, total delay cost for Regulation 1 is lower for MATFM (constrained case) than for CASA (unconstrained case) slot allocation, albeit after some computational effort to reduce otherwise very high MATFM delay cost. It should be noted that we use individual delay cost function for each flight, explicitly differentiating between linear (strategic) and non-linear (tactical) part. Further, the aircraft type mix plays important role, as both strategic and especially tactical costs are much higher for large aircraft than that of the small one. Moreover, tactical costs used in calculation include estimated cost of reactionary delay. While we are able to estimate reactionary delay per flight, there are no such reactionary delay unit cost values provided in

Table 4
Ex post analysis of delay propagation, STW, SPG, AID indicators (in minutes); rounded averages.

	Regulation 1 (MINP)				Regulation 2 (MINP)			
	d^p	d^p (STW)	d^p (SPG)	d^p (AID)	d^p	d^p (STW)	d^p (SPG)	d^p (AID)
CASA	143	202	133	37	198	328	230	65
MINPinf	129	198	120	36	146	304	182	46
MATFM	155	213	143	57	261	389	302	122
MINP	129	198	120	36	197	358	245	73

the literature (Cook and Tanner, 2015). Therefore, we are not in a perfect position to credibly claim which of the two methods – to reduce delay propagation or to minimize ATFM delay – performs better in the cost domain.

While certain net benefits seem to be possible at the network level, the distribution thereof (e.g. per AO) might give rise to equity concerns. Namely, it seems that the benefits in terms or delay minutes and/or cost savings, come at the expense of distributing the ATFM delay over flights with long(er) schedule buffers. From the "*bearing the burden vs. receiving the benefits*" equity standpoint, the MINP model favours more predictable flights at the cost of those with less predictable times of operation. However, MINP policy also favours less predictable operations on the other end, meaning that flights with, for yet unobserved reasons, negative schedule buffer get protected from high(er) ATFM delays. Again, to evaluate the fairness of such operational implications of the policy applied, one has to know the reasons behind the negative buffer. Is the tactical gate-to-gate time longer than scheduled due to a limitation in the airspace (e.g. unavailability of ATM system to provide a shorter route) or it is the policy of an AO to, perhaps, *game the system* (for instance, to advertise otherwise unfeasible transfer connections)? As the answer to this intriguing question lies beyond the scope of this paper, we further discuss the potential consequence on the scheduling practices of AOs, knowing that it usually takes one or two seasons for AOs to adapt their schedules to compensate for anticipated pattern of delays (EUROCONTROL CODA, 2015).

Increasing flights' buffer levels in the presence of MINP-like policy would obviously expose flights to potentially higher ATFM delays in case those flights get regulated. Decreasing buffer levels, on the other hand, would increase the risk of delay propagation and potentially lower punctuality levels, which could decrease AO's attractiveness in the market (Suzuki, 1998). On a related matter, a recent study 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: the results suggest that there are some benefits, from social point of view, if schedule buffers are decreased (de Villemeur et al., 2011). Therefore, decrease in the schedule buffer levels should be supported by airports and airspace capacity suppliers in a manner to enable AOs to maintain, at least, their punctuality levels. Further improved predictable behaviour of AOs, in terms of adherence to filed flight plans, should lead to decreasing equivalent buffers on the capacity side, incorporated to protect ATC sectors from overdeliveries (EUROCONTROL SKYbrary, 2014c). In fact, one ANSP estimated that approximately 5–10% of its capacity is actually 'reserved' to take care of all 'non-adherence issues', arising in pre-tactical and tactical stage, and argue that possible cost saving of a more predictable system could reach 45 million EUR per annum for that provider (EUROCONTROL SKYbrary, 2013). While the application of our model does not increase the cost of capacity provision, estimating potential savings on the capacity side lies beyond the scope of this paper.

In that context, we present an overview and interrelationship of capacity and demand side contingency (buffer) levels decision making. Namely, 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 (Massacci and Nyrup, 2015). 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 (EUROCONTROL, 2014d). 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 (Jovanović et al., 2015). 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.

Lastly, MINP strategy effectively seems to increases average ATFM delay and, as such, might not, at least not instantly, be seen positively from the NM and ANSP, having in mind the SES ATFM delay targets. AO were indeed confronted with more mandatory re-routings in the last couple of years, arguing that this is the way for ANSPs to cut their ATFM delay figures. But from the ATM/ATC perspective, these re-routings might be seen as a measure to prevent increased traffic complexity in some regions or are merely a consequence of some other factors, such as the closure of Ukrainian airspace in 2014 (EUROCONTROL PRC, 2015). To that end, one natural extension of this research could deal with finding a more cost-efficient balance between the confronted objectives of various stakeholders involved, including possibly an appropriate adjustment of associated SES performance targets.

6. Conclusions

This research is based on solid practical grounds and as such is tailored to solving real-life congestion problems in European airspace. First, we recognize the different perspectives of delay, namely Aircraft Operators' (demand side) and ANSPs and NM (supply side) standpoint. We challenge the current First Come First Served principle to minimize ATFM delay, which, although equitable, focuses on delays which are an order of magnitude lower than the delays AOs are concerned about, i.e. propagated delays. Further, we address the problem of airport slot adherence, considering the case when an en-route sector demand-capacity imbalance affects operations from already congested airports. We propose a two-level model, which takes advantage of schedule buffers, i.e. flights' ability to absorb ATFM delay. On the first level of the model, the ATFM slot allocation process minimizes delay propagated to subsequent flights. On the second level, we find such ATFM slot allocation to improve adherence to airport slots, preserving the optimal propagated delay minutes.

Results from two small/medium-scale real-world case studies show that it is possible to use the proposed methodology to lower delay propagated to subsequent flights and at the same time to improve airport slot adherence. In addition, we analyse the problem in the cost domain too. The results suggest that certain delay cost savings are also possible compared to current ATFM slot allocation. Such improvements usually come at the expense of increased ATFM delay minutes. The results suggest that the current regulatory settings, namely binding European Air Navigation Service Providers through the Single European Sky Performance Scheme, to meet ATFM delay targets, are neither necessarily fully aligned with the desires and operating goals of Aircraft Operators, nor they improve the predictability of operations in the network. To that end, the work is already underway on investigating possible improvements of system's cost-efficiency by acting on both supply (adaptive capacity provision) and demand side of the system (product differentiation with innovative pricing), in a re-designed ATM value chain, in an attempt to narrow the gap between planning horizons of AOs and ANSPs, which is believed to be one of the key drivers of cost-inefficiencies in the current system's setting.

Acknowledgments

This research has been initially conducted with the support from Project 36033 research grant of the Ministry of Science and Technological Development of the Republic of Serbia. This project has received funding from the SESAR Joint Undertaking under grant agreement No 699326 under European Union's Horizon 2020 research and innovation programme. Authors would like to thank Chris Peregrine, Nikola's mentor during internship in EUROCONTROL, and particularly Yves De Wandeler from EUROCONTROL CODA for their valuable contribution. Authors thank Andrew Cook for his valuable help regarding delay costs considerations. We also thank anonymous referees for their valuable comments and suggestions. Opinions expressed in this paper reflect authors' views only.

Appendix A. List of acronyms

AID	Absorbed inbound delay
ANSP	Air Navigation Service Provider
AO	Aircraft Operators
APSA	Optimization model for maximizing airport slot adherence
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CASA	Computer Assisted Slot Allocation
CODA	Central Office for Delay Analysis
CS1	Centralised Service 1
CTA	Calculated Time of Arrival
DDR	Demand Data Repository
CTOT	Calculated Take-off Time
DM	Demand Management
EC	European Commission
EOBT	Estimated Off-block Time
ETA	Estimated Time of Arrival
ETOT	Estimated Take-off Time
FAS	Flight Plan and Airport Slot Consistency
FCFS	First Come First Served
FPL	ICAO Flight Plan
H&S	Hub and Spoke
IATA	The International Air Transport Association
ICAO	International Civil Aviation Organisation
KPA	Key Performance Area

(*continued on next page*)

KPI	Key Performance Indicator
LCC	Low Cost Carrier
MATFM	Optimization model for minimizing ATFM delay with capacity constraints
MINP	Optimization model for minimizing delay propagation
NEST	Eurocontrol Network Strategic Tool
NM	Network Manager
PRC	Performance Review Commission
P2P	Point to Point
SES	Single European Sky
SESAR	Single European Sky Air Traffic Management Research
SPG	Schedule padding-ground
STAM	Short-term Air Traffic Flow and Capacity Management Measures
STW	ATFM Slot Tolerance Window

References

Adamson, P., 2015. Optimising airport performance in a network environment. In: CS1 Airport Workshop. EUROCONTROL, Brussels.

Agustin, A., Alonso-Ayuso, A., Escudero, L.F., Pizarro, C., 2012. On air traffic flow management with rerouting. Part I: Deterministic case. Eur. J. Oper. Res. 219, 156–166. http://dx.doi.org/10.1016/j.ejor.2011.12.021.

Agustín, A., Alonso-Ayuso, A., Escudero, L.F., Pizarro, C., 2010. Mathematical optimization models for air traffic flow management: a review. Stud. Inform. Univ. 8, 141–184.

AhmadBeygi, S., Cohn, A., Guan, Y., Belobaba, P., 2008. Analysis of the potential for delay propagation in passenger airline networks. J. Air Transp. Manage. 14, 221–236. http://dx.doi.org/10.1016/j.jairtraman.2008.04.010.

Andreatta, G., Brunetta, L., Guastalla, G., 1997. Multi-airport ground holding problem: a heuristic approach based on priority rules. In: Bianco, L., La Bella, A. (Eds.), Transportation Analysis. Springer, Berlin, Heidelberg, pp. 71–89.

Avenali, A., D'Alfonso, T., Leporelli, C., Matteucci, G., Nastasi, A., Reverberi, P., 2015. An incentive pricing mechanism for efficient airport slot allocation in Europe. J. Air Transp. Manage. 42, 27–36. http://dx.doi.org/10.1016/j.jairtraman.2014.07.009.

Barnhart, C., Fearing, D., Odoni, A., Vaze, V., 2012. Demand and capacity management in air transportation. Eur. J. Transp. Logist. 1, 135–155. http://dx.doi.org/10.1007/s13676-012-0006-9.

Bertsimas, D., Patterson, S.S., 1998. The air traffic flow management problem with enroute capacities. Oper. Res. 46, 406–422. http://dx.doi.org/10.1287/opre.46.3.406.

Bertsimas, D.J., Lulli, G., Odoni, A., 2008. The air traffic flow management problem: an integer optimization approach. In: 3th Int. Conf. Integer ProgramComb. Optim., pp. 34–46. http://dx.doi.org/10.1007/978-3-540-68891-4_3.

Castelli, L., Pellegrini, P., Pesenti, R., Management, D., 2012. Airport slot allocation in Europe: economic efficiency and fairness. Int. J. Revenue Manage. 6, 28–44. http://dx.doi.org/10.1504/IJRM.2012.044514.

Castelli, L., Pesenti, R., Ranieri, A., 2011. The design of a market mechanism to allocate Air Traffic Flow Management slots. Transp. Res. Part C Emerg. Technol. 19, 931–943. http://dx.doi.org/10.1016/j.trc.2010.06.003.

Churchill, A., Lovell, D., Ball, M., 2009. Evaluating a new formulation for large-scale traffic flow management. In: 8th USA/Europe ATM R&D Seminar, Berlin.

Cook, A., 2007. European Air Traffic Management: Principles, Practice and Research. Ashgate Publishing Ltd.

Cook, A., Tanner, G., 2015. European airline delay cost reference values. Final Report. University of Westminster for EUROCONTROL Performance Review Unit.

Cook, A., Tanner, G., Williams, V., Meise, G., 2009. Dynamic cost indexing – managing airline delay costs. J. Air Transp. Manage. 15, 26–35. http://dx.doi.org/10.1016/j.jairtraman.2008.07.001.

Corolli, L., Lulli, G., Ntaimo, L., 2014. The time slot allocation problem under uncertain capacity. Transp. Res. Part C Emerg. Technol. 46, 16–29. http://dx.doi.org/10.1016/j.trc.2014.05.004.

de Villemeur, E.B., Quinet, E., Ivaldi, M., Urdanoz, M., 2011. Optimal air traffic delays. In: 1st SESAR Innovation Days, Toulouse.

Delgado, L., Prats, X., 2012. An en-route speed reduction concept for absorbing air traffic flow management delays. J. Aircr. 49, 214–224. http://dx.doi.org/10.2514/1.C031484.

Etxebarria, I., Regidor, C., Escribano, B., 2013. Intelligent modelling of the air transport network impact of innovative prioritisation strategies on delay patterns. In: 3rd SESAR Innovation Daysation Days, Stockholm.

EUROCONTROL, 2016. NEST User Guide 1.5.1.

EUROCONTROL, 2015a. Network Manager Annual Report 2014.

EUROCONTROL, 2015b. Annual Network Operations Report 2014, Annex I - Airspace Users View.

EUROCONTROL, 2014a. Centralised Service on Flight Plan and Airport Slot Consistency (FAS): Concept of Operations (CONOPS), Edition 2.1.

EUROCONTROL, 2014b. Short-term ATFCM measures: building on the local flow management process [WWW Document]. <http://www.eurocontrol.int/articles/short-term-atfcm-measures-building-local-flow-management-process> (accessed 12.1.15).

EUROCONTROL SKYbrary, 2014c. Sector Over-deliveries and Overloads - SKYbrary Aviation Safety [WWW Document]. <http://www.skybrary.aero/index.php/Sector_Over-deliveries_and_Overloads> (accessed 3.13.16).

EUROCONTROL, 2014d. Network Operational Concept 2019, Ed.1.0.

EUROCONTROL CODA, 2015. All-Causes Delay and Cancellations to Air Transport 2014 - CODA Digest.

EUROCONTROL NMOC, 2016. ATFCM Operations Manual, Ed. 20.0.

EUROCONTROL PRC, 2015. An Assessment of Air Traffic Management in Europe during the Calendar Year 2014 - Performance Review Report.

EUROCONTROL SKYbrary, 2013. Sector Over-Deliveries Due to Non-Adherence/Response [WWW Document]. <http://www.skybrary.aero/index.php/Sector_Over-Deliveries_Due_to_Non-Adherence/Response> (accessed 3.13.16).

European Commission, 2013. Commission Implementing Regulation (EU) No 390/2013 of 3 May 2013 laying down a performance scheme for air navigation services and network functions. OJ L 128, 9.5.2013, pp 1–30.

European Commission, 2011. Commission decision of 21 February 2011 setting the European Union-wide performance targets and alert thresholds for the provision of air navigation services for the years 2012 to 2014. Off. J. Eur. Union L 48/16 (23.2.2011).

European Commission, 2010. Commission Regulation (EU) No 691/2010 of 29 July 2010 laying down a performance scheme for air navigation services and network functions. Off. J. Eur. Union L 201/1 (3.8.2010).

Fukui, H., 2014. Effect of slot trading on route-level competition: evidence from experience in the UK. Transp. Res. Part A Policy Pract. 69, 124–141. http://dx.doi.org/10.1016/j.tra.2014.08.012.

Glover, C.N., Ball, M.O., 2013. Stochastic optimization models for ground delay program planning with equity–efficiency tradeoffs. Transp. Res. Part C Emerg. Technol. 33, 196–202. http://dx.doi.org/10.1016/j.trc.2011.11.013.
Jetzki, M., 2009. The Propagation of Air Transport Delays in Europe. Aachen University.
Jovanović, R., Babić, O., Tošić, V., 2015. Pricing to reconcile predictability, efficiency and equity in ATM. In: 11th USA/Europe ATM R&D Seminar, Lisabon.
Jovanović, R., Tošić, V., Čangalović, M., Stanojević, M., 2014. Anticipatory modulation of air navigation charges to balance the use of airspace network capacities. Transp. Res. Part A Policy Pract. 61, 84–99. http://dx.doi.org/10.1016/j.tra.2014.01.005.
Kuhn, K.D., 2013. Ground delay program planning: delay, equity, and computational complexity. Transp. Res. Part C Emerg. Technol. 35, 193–203. http://dx.doi.org/10.1016/j.trc.2013.07.008.
Leal de Matos, P.A., Powell, P.L., 2003. Decision support for flight re-routing in Europe. Decis. Support Syst. 34, 397–412. http://dx.doi.org/10.1016/S0167-9236(02)00066-0.
Levinson, D., Rafferty, P., 2004. Delayer pays principle examining congestion pricing with compensation. Int. J. Transp. Econ. 31, 295–311.
Liu, Y., Hansen, M., 2013. Ground delay program decision-making using multiple criteria: a single airport case. In: 10th USA/Europe ATM R&D Seminar, Chicago.
Lulli, G., Odoni, A., 2007. The european air traffic flow management problem. Transp. Sci. 41, 431–443. http://dx.doi.org/10.1287/trsc.1070.0214.
Madas, M.A., Zografos, K.G., 2008. Airport capacity vs. demand: mismatch or mismanagement? Transp. Res. Part A Policy Pract. 42, 203–226. http://dx.doi.org/10.1016/j.tra.2007.08.002.
Massacci, R., Nyrup, F., 2015. Challenges facing the ANSPs – future demand management for MUAC. In: 2nd SATURN Workshop. 2nd SATURN workshop, London.
Mayer, C., Sinai, T., 2003. Why Do Airlines Systematically Schedule Flights to Arrive Late? The Wharton school, University of Pennsylvania, USA.
Montlaur, A., Delgado, L., 2015. Delay assignment optimization strategies at pre-tactical and tactical levels. In: 5th SESAR Innovation Days, Bologna.
Pellegrini, P., Castelli, L., Pesenti, R., 2012. Secondary trading of airport slots as a combinatorial exchange. Transp. Res. Part E Logist. Transp. Rev. 48, 1009–1022. http://dx.doi.org/10.1016/j.tre.2012.03.004.
Ranieri, A., Alsina, N., Castelli, L., Bolic, T., Herranz, R., 2013. Airport slot allocation: performance of the current system and options for reform. In: 3rd SESAR Innovation Days, Stockholm.
SESAR Consortium, 2012. European ATM Master Plan - Edition 2.
Suzuki, Y., 1998. The relationship between on-time performance and profit: an analysis of U.S. airline data. J. Transp. Res. Forum 37.
Tošić, V., Babić, O., Čangalović, M., Hohlačov, D., 1997. A model to solve en route air traffic flow management problem: a temporal and spatial case. In: 1st USA/Europe Air Traffic Management Research and Development Seminar, Saclacy, pp. 1–8.
Tošić, V., Babić, O., Čangalović, M., Hohlačov, D., 1995. Some models and algorithms for en route air traffic flow management. Transp. Plan. Technol. 19, 147–164. http://dx.doi.org/10.1080/03081069508717564.
Transportation Research Board, 2011. Equity of evolving transportation finance mechanisms, Special Re. ed. Washington, D.C.
Van Der Veldt, T., 2015. Flight efficiency now: establishing common objectives. In: Network Manager User Forum 2015, Brussels.
Vranas, P.B.M., Bertsimas, D., Odoni, A.R., 1994. The multi-airport ground-holding problem in air traffic control. Oper. Res. 42, 249–261. http://dx.doi.org/10.1287/opre.42.2.249.
Wandeler, Y. De, 2014. Building the delay-analysis system for Europe. In: ICAO Business Class Symposium, Montréal.
Wu, C.-L., 2005. Inherent delays and operational reliability of airline schedules. J. Air Transp. Manage. 11, 273–282. http://dx.doi.org/10.1016/j.jairtraman.2005.01.005.