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Reducing ATFM delays through strategic flight planning

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ABSTRACT

This paper presents an integer programming model for strategic redistribution of flights so as to respect nominal sector capacities, in short computation times for large-scale instances. The main contribution lies in the combination of tackling large-scale strategic flight planning using hard capacity constraints, while considering the whole network (i.e., both airports and sectors). Real historic data for network and traffic description are used for our test instance. Strategic and tactical impact assessments show that early flight planning can lead to the reduction of delays and their costs, showing potential for actual implementation.

1. Introduction

Air Traffic Flow Management (ATFM) ensures "that capacity is utilised to the maximum extent possible, and that the traffic volume is compatible with the capacities declared by the appropriate air traffic service providers" (EUROCONTROL ATM Lexicon, 2016). The European ATFM system currently offers a high level of flexibility to airlines with regard to flight planning. Flight plans need to be submitted tactically, a few hours before the operation of flights, which enables airlines to take into account many uncertain factors (e.g., weather) and create the most convenient flight plan for them. However, this flexibility comes at a cost of ATFM delays.[1] When submitting a flight plan, the airlines do not have the information on airspace nominal capacities and do not need to consider it. Tactical submission of flight plans results in the traffic load (demand) on the airspace network being known only on the day of operations, while the capacity provision (mostly related to staffing levels) is typically planned a year in advance and updated a few days before. Then, whenever available airspace (and airport) capacity cannot accommodate the air traffic on the day of operations, ATFM measures are agreed upon and implemented through the *regulations*.[2] Regulations enforce thus established capacity limits, by assigning ground delay (i.e. ATFM delay) to flights planned to enter congested elements of the network (EUROCONTROL, 2016). In case no regulations are invoked, en-route capacity is not enforced.

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[1] ATFM delay is defined as "the duration between the last take-off time requested by the aircraft operator and the take-off slot allocated by the Central Flow Management Unit (CFMU) following a regulation communicated by the Flow Management Position (FMP), in relation to an airport (airport delay) or sector (en-route delay) location" (EUROCONTROL ATM Lexicon). Note that CFMU is now called Network Manager Operations Centre (NMOC), often shortened to Network Manager.

[2] Regulations are "a method of matching traffic demand to available capacity by limiting the number of flights planned to enter an airspace or aerodrome, achieved by the issuing of departure slots" (EUROCONTROL ATM Lexicon).

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The amount of ATFM delays and the related cost are significant: the average ATFM delay in Europe in 2014 was 1.03 min/flight, and 1.42 min/flight in 2015 (EUROCONTROL, 2015); these were due to either airport or en-route related issues. Considering an average ATFM delay cost of 100 €/min (Cook and Tanner, 2015), these average delay figures translate to costs that exceed 1 B€ per year. In the past five years, en-route delay[3] accounted for 50–60% of total ATFM delay, while the rest was accrued at the airports. The major share (46% in both 2014 and 2015 (EUROCONTROL, 2015)) of the en-route ATFM delay was due to the air traffic control (ATC) capacity, meaning that the available capacity of a portion of airspace was below the traffic demand.

One of the reasons behind such demand-capacity imbalances is the insufficient information sharing, especially on demand. The European Air Traffic Management (ATM) Master Plan foresees earlier (strategic) sharing of information by all stakeholders, with the goal to improve the predictability of the system (SESAR, 2015). Another reason lies in the fact that the capacity is generally managed in a tactical way. Nowadays in Europe, the only mechanism used to manage air traffic capacity strategically (i.e., months in advance) is the airport slot allocation which takes place before the beginning of each season, following International Air Transportation Association's worldwide slot guidelines (IATA, 2015). Slots are needed by airlines in order to operate flights to and from congested airports and need to be obtained prior to the publication of the seasonal schedule. Thus, strategically, the origin and destination airports, departure/arrival times and aircraft types are known. In contrast, the flight route information that gives more detail on the airspace demand becomes available only in the tactical phase, leaving little to no time to Air Navigation Service Providers (ANSPs) to adjust the capacity provision, which results in the imposition of regulations and consequent delays.

With this in mind, this work first proposes an integer programming model to implement strategic flight planning. The goal is to provide a distribution of traffic that respects the *declared nominal capacities* of airports and sectors on the entire network, in order to alleviate demand-capacity imbalances already at the strategic level. Such traffic distribution can reduce the amount of ATFM delays imposed on the day of operations in two ways. On one hand, by eliminating the imposition of ATFM delay to respect nominal capacities, as those are already balanced by the mechanism. On the other hand, by lowering the amount of delay due to other types of regulations that impose limitations stricter than the declared nominal capacity. The causes of such regulations can usually be known only on the day of operations (e.g., weather regulations). Even in this case, strategic traffic redistribution could result in smaller delays as the number of flights exceeding imposed capacity would be smaller than today, as the nominal capacity is practically not enforced. Thus, a strategic redistribution of air traffic has a potential to lower the number of ATFM interventions on the day of operations.

Since the usefulness of an early traffic assignment holds as long as delays and associated costs for airlines in the tactical phase are likely to be reduced, in the next step of this work the tactical impact of the strategic plans is simulated and evaluated in terms of delay and related costs. The evaluation is performed by comparing results to those of scenarios where no capacity constraints are enforced. We show that with the proposed approach the number and magnitude of interventions that regulations impose on the day of operations would be reduced.

Literature proposing solutions for the strategic demand management of airport capacity through the use of airport slots is quite extensive; see for example Zografos et al. (2013) for a comprehensive review of the state-of-the-art. A recent work by Jacquillat and Odoni (2015) introduces an integrated approach to airport congestion that jointly optimises strategic scheduling interventions and tactical airport capacity utilisation. To do so, the authors propose an integrated model that combines a stochastic queuing model of congestion, a dynamic programming model to control resource utilisation, and an integer programming model for scheduling. Results indicate that very substantial delay reductions can be achieved through limited changes in airline schedules. Although specific to the United States context and limited to the analysis of a single heavily operated airport, this work supports the validity of strategic planning as a means to reduce ATFM delay.

Conversely, literature on airspace congestion and measures to prevent it mainly addresses tactical problems, as with the flight plan filing systems in place, the congestion becomes apparent only tactically. The most studied tactical problem is the ATFM problem, which is aimed at defining ground holding, airborne holding, and rerouting actions to be applied to flights on the day of operations. The ATFM problem was first formalised by Odoni (1987). Many studies of the ATFM problem, building on Odoni's work, have been published since. Bertsimas and Stock Patterson (1998, 2000) introduced speed control and rerouting. Andreatta et al. (1998) proposed an exact algorithm to solve instances of the ATFM problem with over 20,000 flights from the U.S. air traffic system in less than 20 min. However, the model takes only airports into account, without considering airspace sector capacities. Lulli and Odoni (2007) studied the European ATFM problem, including the concept of fairness in the objective function. Bertsimas et al. (2011) proposed a model for large-scale instances (about 6,500 flights) that includes ground and airborne holding, rerouting, and speed control. Based on this work, Castelli et al. (2011) identify which flights are likely to produce undesired downstream effects if subjected to delay. Review papers are also available, see Agustín et al. (2010) and Hoffman et al. (2011). Recent advances include the development of metrics (Barnhart et al., 2012) and optimisation approaches (Bertsimas and Gupta, 2016) to define an equitable distribution of delays among stakeholders. Strategic level airspace congestion problems are based on pricing mechanisms,

[3] ATFM en-route delay is defined as "ATFM delay caused by regulations applied by the CFMU at the request of the FMP to protect en-route ATC sectors from overload (EUROCONTROL ATM Lexicon).

as in Europe aircraft operators have to pay air navigation charges to ANSPs for the services they receive. Andreatta and Odoni (2001) investigated the possibility to modulate air navigation charges to reflect the presence of airspace congestion. Along the same line, Bolić et al. (2017) extend the use of peak-load pricing to the context of the European ATM system. In Raffarin (2004) and Jovanović et al. (2014) alternative pricing rules for air navigation charges are proposed, based on the idea of giving airlines economic incentives to modify their behaviour, so that the resulting routing choices are optimal from both social and individual points of view. A logit-based price levels assignment model to reduce airspace congestion is illustrated in Deschinkel et al. (2002).

The formulation of the model for strategic flight distribution presented in this paper is a strategic adaptation of the ATFM model by Bertsimas et al. (2011). As a first variation, airborne holding and speed control are not allowed, as these are control options used only in actual operations. Hence, it is possible to assign the entire route from origin to destination instead of building it segment-by-segment. In other words, our model uses a route-based formulation (in a very convenient situation where enumerating routes is not problematic) while ATFM uses an arc (i.e., sector)-based formulation. In addition, our formulation is able to address circumstances that may occur when dealing with actual data, as for instance the fact that geometry of sectors and routes may cause a flight to enter/exit a sector multiple times. Further, the departure times can be assigned after, but also before the requested times, as the application is strategic. Finally, as different sets of sectors can be active at different times, the dynamic configuration of the network is explicitly considered. To the best of our knowledge, this work represents the first attempt at defining strategic traffic distribution by strictly enforcing sector capacity constraints using an optimisation model, on a realistic air traffic network. The proposed strategic model is able to deal with large-scale instances that include around 30,000 flights, which, to the best of our knowledge, is significantly more than previous literature considered.

The mathematical formulation of the model is presented in Section 2. The following Section 3 describes the definition of the experimental design for demonstration and analysis of strategic and tactical impact of our model. The model is applied on real data that include all flights from one busy day of operations in Europe (i.e., around 30,000 flights). Section 4 investigates the impact of strategic flight planning, resulting from the model application on the problem instance. Then, in Section 5, the tactical impact of using strategic flight plans is evaluated through the simulation of ATFM delays. Finally, in Section 6, the conclusions and future directions of work are drawn.

2. Integer programming formulation for strategic flight planning

The goal of our strategic model is to re-distribute traffic in such a way that the nominal declared capacities are respected. The model is centralised, meaning that all the information needed for the model is collected and the system optimum is sought. This approach is consistent with current practice (albeit only tactically), and the planned strategic information sharing in the form of the Network Operations Plan (SESAR, 2015). From the implementation point of view, this entails having a Central Planner (CP) collecting all the information, and running the model. The information needed comprises of: sector configurations and capacities from ANSPs, while the airlines would need to submit their preferred departure and arrival times, alternative routes and aircraft type. In Europe, these data are already being shared with the Network Manager, usually only a few hours before the flights are scheduled to depart. Model results represent strategic flight plans for all scheduled flights. We assume that all the information should be submitted to the CP within a deadline, before the publication of seasonal schedules.

The model we propose has the following characteristics:

- **Strategic shift of operations.** As the model is applied in the strategic phase, before flight schedules are published, departure and arrival times earlier or later than the requested ones may be assigned. For this reason, when assigned times differ from requested times, we talk about schedule "shifts" rather than "delays", which instead are dealt with in the tactical phase of operations.
- **Control of possible shift for airport movements.** To avoid excessive shifting, the maximum allowed shift to earlier or later departure/arrival times is bounded.
- **No flight cancellations.** All flights are assigned a strategic flight plan.
- **Departure time and route choice control.** The model assigns the departure time and route for each flight. The route is chosen from the alternative routes specified by the airlines, with each route specifying the complete set of sectors to cross from origin to destination. Speed control is not taken into consideration, as it would make little sense in the strategic phase. Hence, the duration of each route is assumed to be constant, and sector entry and arrival times are uniquely identified for each route/departure time option.
- **Dynamic sectorisation.** The configuration of the airspace changes throughout the day, and our model takes into account the evolution of sector openings/closures over the considered time horizon. A sector is considered active if it is open, inactive otherwise.
- **Re-entering a sector is allowed.** Since flights may enter a sector more than once because of the sector shape or general airspace configuration, the formulation allows multiple entries in any sector.
- **Discrete time precision.** The time horizon is subdivided into discrete time periods of size of choice.

- **Strategic capacity availability.** Similarly to tactical capacity limitations in ATFM models, strategic (nominal) capacities for all flight actions, i.e., departure, arrival, and total airport movements,[4] are defined, limiting the number of corresponding actions within a given time horizon (typically 1 h). The same applies to sectors, where capacity limits the number of possible entries in a time horizon, following the European definition of sector capacity.

The notation, decision variables, and objective function of the model are defined next.

2.1. Notation

The proposed model requires the definition of the following notation:

F	set of flights, indexed by f
K	set of airports, indexed by k
A	set of aircraft types, indexed by a
a_f	aircraft type used to perform flight f
O	set of origin-destination (OD) pairs, indexed by o
o_f	OD pair connected by flight f
S	set of sectors, indexed by s
R	set of routes, indexed by r
$R_o^a \subseteq R$	set of routes that may be used by a flight operating between OD pair o with aircraft type a
n_r	number of elements (sectors and airports) along route r
s_r^i	i-th element (airport or sector) of route r
B	set of flight actions, B = {*ent*, *dep*, *arr*, *tot*}, where *ent* is an entry into a sector, and *dep*, *arr*, and *tot* are departure, arrival, and total (i.e., departure or arrival) airport movements, respectively
T	set of time periods at which flight actions are considered
E	set of elements $S \cup K$ (sectors and airports), indexed by j
H	set of hours, indexed by h
TA_j^h	set of time periods in hour h in which element j is active
$Q_{b,j}^h$	maximum number of flights that may perform action b at element j in hour h *(i.e., capacity)*
dt_f	requested departure time of flight f
at_f	requested arrival time of flight f
$\mathrm{T_f^r}$	set of time periods allowed for departure for flight f along route r
$orig_o$	origin airport of OD pair o
$dest_o$	destination airport of OD pair o
l_r^i	flight time from origin to the i-th element of route r

The trajectory of a flight is defined through a route $r \in R$. All the sectors that a flight may traverse following route r are given in the s_r^i structure, where they are sequenced on the order in which a flight traverses them. The time of execution of a flight action (i.e., departure, arrival, or sector entry) is identified by flight $f \in \mathrm{F}$ and element index $\mathrm{i} \in [1, \mathrm{n_r}]$. This is different from the formulation commonly adopted in ATFM models, where trajectories are identified in terms of flight f and airport/sector $j \in \mathrm{S} \cup \mathrm{K}$ only (see for example Bertsimas et al., 2011). Our notation uses element indexing instead of sector/airport names, preventing inconsistencies that may arise due to the need to enter a sector multiple times along the same route, as this is observed in practice (see Fig. 1).

Further, our notation allows for more precise trajectory representation. In a "classic" ATFM notation, the time needed to reach sector B after entering sector A is the same along all routes that contain sectors A and B, where A immediately precedes B. With our notation, it is possible to distinguish between a route in which t' time periods are needed to traverse sector A and enter sector B, and another route where the needed time is t'', with $t' \neq t''$. This situation is not uncommon in practice, as it may simply correspond to two different routes that traverse the same pair of sectors (e.g., they might have different lengths within the same sector).

2.2. Decision variables

The following set of decision variables is used in the proposed model:

$$x_r^f(t) = \begin{cases} 1, & \text{if flight } f \text{ departs at time period } t \text{ following route } r; \\ 0, & \text{otherwise.} \end{cases} \quad \forall f \in F,\ r \in R_{o_f}^{a_f},\ t \in T_f^r \tag{1}$$

[4] The distinction between departure, arrival and total capacities is introduced because in many European airports the number of allowed total (departure + arrival) movements, within a given time horizon, is less or equal to the sum of departure and arrival capacities.

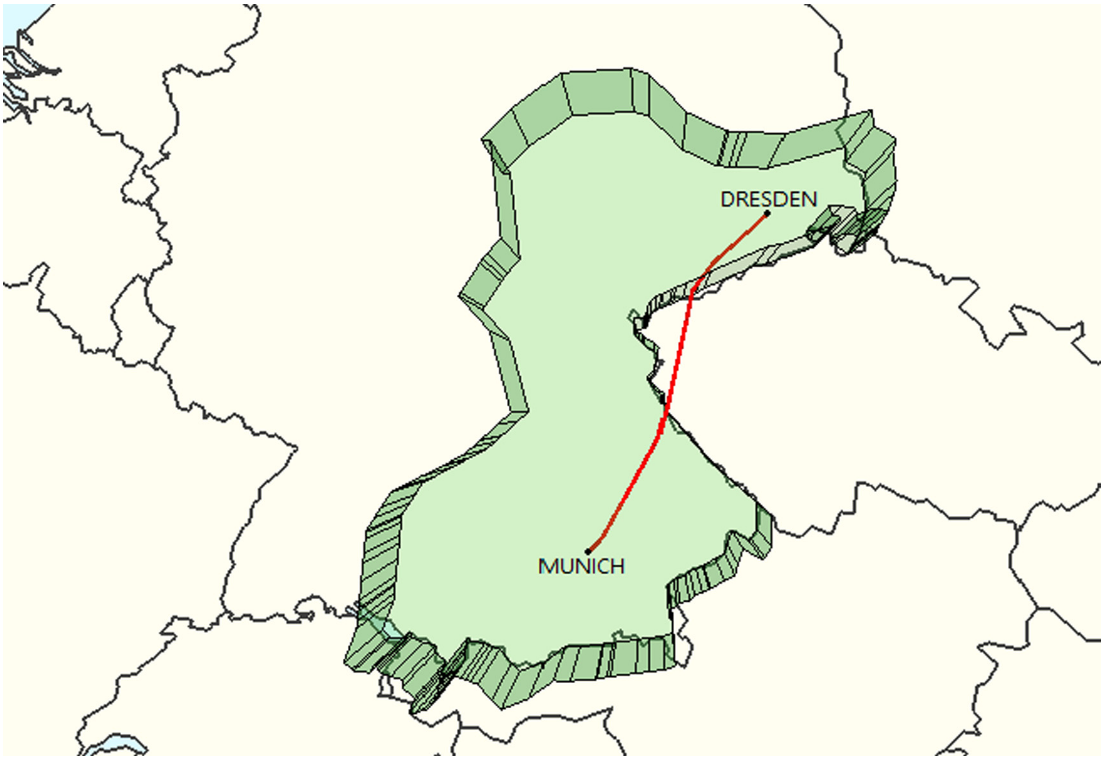

Fig. 1. Flight from Munich to Dresden, exiting and entering the same sector. *Source*: NEST air traffic data visualisation tool.

The decision variables represent the assignment, as allocated by the CP, of departure time t and route r, for each flight. Since all flights are assigned a departure time and route (i.e., no flights are cancelled), only one decision variable per each flight will be equal to 1, and all other variables will be equal to 0.

2.3. Objective functions

Strategic flight plans can be obtained using two alternative objectives:

- **Shift minimisation (MS – minimum shift):** the total schedule shift of flights is minimised.
- **Flight operational cost minimisation (MC – minimum cost):** the total operational cost of flights is minimised.

2.3.1. Shift-based objective function (MS)

The shift-minimisation objective function sums the negative departure and positive arrival shifts per flight. These are the minutes of earlier-than requested departures and later-than requested arrivals respectively. Such a definition prevents from counting twice the shift that is propagated from departure to arrival or vice versa.

To guarantee equity in the assignment of strategic flight plans, we adopt the well-known approach used by Lulli and Odoni (2007). Their approach ensures equity by including in the objective function cost coefficients that are a superlinear function of the quantity that should originally be minimised for each flight (in their case the tardiness of a flight, in our case the flight shift). That is, instead of minimising the summation over all flights of some coefficients c_f, these coefficients are accounted for under the form $c_f^{1+\epsilon_1}$, with $\epsilon_1 > 0$ and close to zero (Bertsimas and Gupta, 2016). The use of these coefficients favours "the assignment of a moderate amount of delay to each of two flights rather than the assignment of a small amount to one and a large amount to the other" (Lulli and Odoni, 2007).

Given some $\epsilon_1 > 0$, the objective function is thus formalised as follows:

$$Min \sum_{f \in F} \left(\sum_{r \in R_{o_f}^{a_f}, t \in T} x_r^f(t) \cdot (\max\{dt_f - t, 0\} + \max\{dt_f + t + l_r^{n_r} - at_f, 0\})^{1+\epsilon_1} \right) \tag{2}$$

The two terms multiplied by $x_r^f(t)$ describe the assigned departure negative shift and arrival positive shift, respectively. For simplicity, the departure negative and arrival positive shifts are referred to as "departure shift" and "arrival shift" in the following text.

2.3.2. Cost-based objective function (MC)

The cost-minimisation objective function aims at minimising flights' strategic operational costs. These are all the costs that can be accounted for in advance and consist of ground and airborne operation costs, and en route charges. The estimation of the strategic unit ground and airborne costs is based on the strategic coefficients and values defined in the report by Cook and Tanner (2015).

- Strategic ground costs are calculated as the unit ground cost (cg_a: cost of 1 min of ground operation of aircraft type a) times the undesired amount of time the flight has to remain grounded, i.e., the shift τ. These costs include ground maintenance, fleet and crew utilisation costs (Cook and Tanner, 2015, Table 9).
- Strategic airborne costs are calculated as the unit airborne cost (ca_a: cost of 1 min of airborne operation of aircraft type a) times the flight duration (l_r^i). These costs include airborne maintenance, fleet and crew utilisation, and fuel costs (Cook and Tanner, 2015, Table 11).
- Route charges (cr_a^r: route charges for a flight operated by aircraft type a on route r) are the means of financing of European ANSPs, and are levied for each flight in the European airspace. They are calculated as the product of the distance factor (distance flown in ANSP's airspace), weight factor, and the unit rate (which varies across ANSPs), as defined by EUROCONTROL's Central Route Charges Office (2015).

Hence, similarly to other approaches already proposed in literature (see for example Bertsimas et al., 2011 and Castelli et al., 2013), the strategic cost to operate a flight with aircraft type a along route r with τ minutes of shift ($c_a^r(\tau)$) is calculated as follows:

$$c_a^r(\tau) = cg_a \cdot \tau + ca_a \cdot l_r^{n_r} + cr_a^r \tag{3}$$

To guarantee equity, we follow the same approach as that used in the MS objective function, using superlinear cost coefficients by raising flight costs to the power of $1 + \epsilon_2$, with $\epsilon_2 > 0$ and close to zero. The cost-based objective function of the problem is then:

$$Min \sum_{f \in F, r \in R_{o_f}^{a_f}, t \in T} c_{a_f}^r (|t - dt_f|)^{1+\epsilon_2} \cdot x_r^f \tag{4}$$

2.4. Constraints

The constraints of the model are illustrated in the following.

$$\sum_{\substack{f \in F, r \in R_{o_f}^{a_f}:\ orig_{o_f} = k, \\ t \in TA_j^h}} x_r^f(t) \leqslant Q_{dep,k}^h \quad \forall k \in K,\ h \in H \tag{5}$$

$$\sum_{\substack{f \in F, r \in R_{o_f}^{a_f}:\ dest_{o_f} = k, \\ t + l_r^{n_r} \in TA_j^h}} x_r^f(t) \leqslant Q_{arr,k}^h \quad \forall k \in K,\ h \in H \tag{6}$$

$$\sum_{\substack{f \in F, r \in R_{o_f}^{a_f}:\ orig_{o_f} = k, \\ t \in TA_j^h}} x_r^f(t) + \sum_{\substack{f \in F, r \in R_{o_f}^{a_f}:\ dest_{o_f} = k, \\ t + l_r^{n_r} \in TA_j^h}} x_r^f(t) \leqslant Q_{gen,k}^h \quad \forall k \in K,\ h \in H \tag{7}$$

$$\sum_{\substack{f \in F, r \in R_{o_f}^{a_f}, \\ i \in [2, n_r - 1]:\ s_r^i = s, \\ t + l_r^i \in TA_j^h}} x_r^f(t) \leqslant Q_{ent,k}^h \quad \forall s \in S,\ h \in H \tag{8}$$

$$\sum_{r \in R_{o_f}^{a_f}, t \in T} x_r^f(t) = 1 \quad \forall f \in F \tag{9}$$

$$x_r^f(t) \in \{0, 1\} \quad \forall f \in F, \; r \in R_{o_f}^{a_f}, \; t \in T_f^r \tag{10}$$

Constraints (5)–(7) enforce the departure, arrival, and total airport capacity constraints, respectively. Total airport movements include both departures and arrivals. Similarly, sector capacity constraints are defined by (8). Since the formulation we propose takes into account the dynamic configuration of the airspace, capacity constraints are defined only for active sectors. Each sector may open and close several times during a day, and each opening interval is defined by the T_j^i set, which includes all time instants in the i-th opening of sector j. Finally, Eqs. (9) and (10) enforce the choice of a single departure time instant and route for each flight, provided that the decision variables $x_r^f(t)$ are binary.

3. Experimental design

This section introduces the experimental design employed for our strategic and tactical analysis. First, the scenarios under which the model and the tactical analysis are run, namely *baseline* and *solution*, are defined. Then, the input data are described. Finally, the indicators used to assess the solutions are illustrated.

3.1. Scenarios

In order to evaluate the solutions obtained from the model, a *baseline* scenario is defined for comparison. Historical data on flight intentions or first filed flight plans would be a logical candidate; however, traffic data we have access to comprise last filed flight plans only, which are tactical, as they are filed a few hours before the flight. Thus, these data take into account perturbations and ensuing regulations that are not known in the strategic phase. This fact makes the last filed flight plans unsuitable for a *baseline* scenario. A more suitable *baseline* scenario is obtained by applying the strategic model, in both MS and MC variants, with unconstrained capacities, which is consistent with the current practice of not considering capacity in the strategic phase. Baseline scenarios *de facto* correspond to a simple assignment of routes of minimum duration or minimum cost, disregarding capacities.

The following scenarios are developed:

- *Baseline*:
  - Minimum duration route (BMD): routes of minimum duration are assigned to flights, at the requested departure times; capacities are not enforced.
  - Minimum cost route (BMC): minimum cost routes are assigned to flights, at the requested departure times. Some arrival shift is possible (if the chosen route is longer than the shortest duration route); capacities are not enforced.
- *Solution*:
  - Minimum shift (SMS): model solved using the minimum shift objective function.
  - Minimum cost (SMC): model solved using the minimum cost objective function.

The BMC and SMC scenarios consider actual flight costs, the definition of which is discussed in Section 3.2.4.

The flight schedules obtained from these four scenarios are used in both strategic and tactical analyses. Flight schedules obtained from baseline scenarios mimic the current situation where the airspace users file flight plans without the need to respect the capacity limits. Flight schedules obtained from the solution scenarios respect nominal declared capacities. Strategic impact analysis compares flight schedules from baseline and solution scenarios, in the idealised situation, without any regulations. Differently, tactical impact analysis compares the impact of regulations on the current-like flight schedules (obtained from baseline scenarios) to the impact on schedules that respect nominal capacities (from solution scenarios).

3.2. Input data

The model is applied on a day of real air traffic data across the entire European airspace. Different data items are needed to run the models, including flights, airspace configuration, capacities of resources (sectors and airports), routes, aircraft types and their operational costs, fuel costs, unit rates, and airline types. The data on air traffic and air network structures are sourced from EUROCONTROL's Demand Data Repository 2 (DDR2). Cost data are taken from the report by Cook and Tanner (2015).

3.2.1. Flights

The air traffic data are taken from September 12th 2014, the fourth busiest day of 2014, selected as not unduly disrupted by unusual events. Military, overflights, helicopters, and flights departing and arriving at the same airport are excluded, resulting in 29,270 flights out of the 33,810 accounted for in the historical data for the day.

3.2.2. Airspace configuration and capacities of resources

In some portions of the airspace, the configuration of the active sectors may change several times throughout the day. This depends mainly (but not only) on the planned traffic flows. The model applies dynamic configurations, and in this specific instance, the configuration in place in Europe on September 12th 2014 is used. The network consists of 204 airports and 1,182 sectors. Furthermore, information on capacity is also needed to define the capacity constraints for airports and active sectors. DDR2 data contain information on airport and sector nominal capacities, which are included in our input data as well.

3.2.3. Aircraft types and related flight costs

A detailed assessment of strategic and tactical operational costs for crew, fuel, aircraft and fleet maintenance for 15 of the most commonly used aircraft in Europe can be found in a report by Cook and Tanner (2015). Three strategic cost profiles are estimated for each of the 15 aircraft, namely *low*, *base* and *high*. In order to estimate operational *strategic* costs for each flight, all aircraft used in the actual traffic data are grouped into 15 clusters, using the 15 reference types as cluster centroids. The square root of the maximum take-off weight (MTOW) is used as the clustering criterion. MTOW values are taken from EUROCONTROL's NEST (Network Strategic Tool) software.

3.2.4. Airline types and cost profiles

Airlines are subdivided into four types: full-service, low-cost, charter, and regional. Based on this subdivision, flights can be grouped into three different flight cost profiles, as follows:

- Low profile: all low-cost carrier (LCC) flights.
- High profile: all full-service carrier (FSC) flights into a hub airport, and regional flights into a hub airport.
- Base profile: all other flights.

ACI EUROPE's "Group 1" airports are used as hub airports. These are the 14 European Civil Aviation Conference (ECAC) airports (excluding the two non-ECAC Moscow airports) with over 25,000,000 passengers in 2014. The cost profiles are used to define flight costs in the BMC and SMC scenarios. Using these subdivision rules, 17% of flights have a low cost profile, 28% a high cost profile, and the rest (55%) have a base cost profile.

3.2.5. Routes and departure times

The set of routes available per OD pair-aircraft type triple is determined through a clustering process on historical flight data from the two weeks preceding September 12th, 2014. Only routes differing significantly from one another in terms of geographical distance (specifically, more than 20 km in the points where the distance between the two routes is maximal, measured in 3-dimensional space) are taken in consideration. This reduces the number of viable routes per OD-aircraft type triple from the tens available in the data to an average of 3.7 routes per triple. Allowed departure times range between 30 min before and 30 min after the time originally requested for each flight. A strategic flight plan is given by the combination of a departure time and 3D route, expressed as a set of crossed sectors.

3.2.6. Route charges and unit rates

Unit rate values for the month of September 2014 for all Contracting States to the Multilateral Agreement relating Route Charges (EUROCONTROL Central Route Charges Office, 2015) are sourced from EUROCONTROL's website. Estonia and Ukraine are also included in the experimental data as their integration in route charging system is underway. The unit rate values for these two states are sourced from the respective ANSP websites.

3.3. Assessment indicators

The model defines strategic flight plans that redistribute traffic both in time (shifts in departure and/or arrival times) and space (alternative 3D routes) when the expected demand overcomes the nominal capacities of sectors and airports. Even though bottlenecks are avoided, the resulting traffic pattern affects other, as important, phenomena. Therefore, a comprehensive assessment takes into account other indicators and looks into the resulting trade-offs. The indicators taken into account are the following:

1. *Departure shift.* Absolute difference between the requested and assigned departure time.
2. *Arrival shift.* Absolute difference between the arrival time obtained by departing at requested departure time using the route of minimum duration and the assigned arrival time.
3. *Flight operational costs.* Based on the cost data found in (Cook and Tanner, 2015), the cost of operation of flights is calculated considering the assigned routes and strategic shifts.
4. *Charges per flight*. This indicator measures the route charges imposed on flights.
5. *Sector capacity utilisation.* This indicator shows for each open sector the capacity utilisation, measured as the number of sector entries over the declared capacity during the chosen time interval (e.g., 1 h).

4. Results analysis: evaluation of the strategic impact

The present section illustrates the results of the strategic flight plans assignment in terms of traffic distribution over airspace sectors, shifts and re-routings applied to flights, and the estimated strategic operational costs. The proposed model was solved for each of the baseline and solution scenarios described in Section 3.1 (BMD/BMC and SMS/SMC respectively).

Experiments were run on a 64 bit Intel(R) Xeon(R) E5520 @ 2.27 GHz quad core CPU computer with 16 GB of RAM memory and Debian 8.0 operating system. The model was implemented in the Mosel language and solved through the Xpress solver, v.8.0. For each instance solved, the optimality gap was set to 1%.

The SMS and SMC problems have the same variables and constraints, but different objective functions. Time precision was set to 1 min, i.e., discrete time intervals are 1 min long. This precision resulted in both problems having 49,573 constraints and 5,901,590 variables. The computation time was 250 s for SMS, and 306 s for SMC, respectively. The capacity-unconstrained baseline counterparts are simple flight plan assignments based on either minimum duration or minimum cost criterion, which are performed in a few seconds for both scenarios.

4.1. Sector capacity utilisation

Fig. 2 shows the distribution of sector capacity utilisation across the considered scenarios. As previously mentioned, for each sector and hour (i.e., sector-hour) with constrained capacity, the capacity utilisation is defined as the ratio of sector entries over declared capacity for that hour. For each sector capacity utilisation level category, the percentage of sector-hours that fall within the category is shown. For example, 0–20 shows the percentage of sector-hours that have a load between 0% and 20%.

As can be seen, the vast majority of sector-hours is not congested – almost 60% of the sector-hours has the capacity utilisation of 40% or less. Furthermore, sector capacity utilisation is very similar across all scenarios from 0% up to 80%. The percentage of capacity constraints (i.e., sector-hours) that are breached in the two baseline scenarios is 2.4% for BMC and 2.1% for BMD. Solution scenarios redistribute traffic in such a way that the capacity constraints are respected. The traffic is shifted to the sector-hours in the category of 80–100% capacity utilisation. This is to be expected as congestion is a localised phenomenon, but high-density traffic areas span across multiple contiguous sectors. Traffic redistribution is therefore mostly performed across these sectors.

A closer inspection of the congested sector-hours reveals that in each hour of the day there are no more than 60 sectors that are congested. The upper panel of Fig. 3 depicts the distribution of sector-hours with capacity utilisation greater than or equal to 100%, across baseline and solution scenarios. In the solution scenarios, the capacity utilisation cannot be higher than 100%, differently from the baseline. As can be seen, the solution scenarios provide lower number of congested sector-hours. When compared to BMC, SMC scenario lowers the number of congested sector-hours slightly, while a more marked decrease can be noted between BMD and SMS scenarios. The excess traffic is redistributed to other sector-hours, mostly in the category 80–100% utilisation. The lower panel of Fig. 3 shows the distribution of sector-hours with capacity utilisation of 90% or more. Even in this case, the number of sector-hours with utilisation of 90% or more is lower in solution scenarios when compared to the baseline scenarios, indicating that the solution scenarios move traffic not only to sectors with utilisation between 90% and 100%, but also to sectors with utilisation lower than 90%. We performed the *t*-test on the capacity utilisations of coupled baseline and solution scenarios (i.e., BMD vs SMS and BMC vs SMC) for these utilisation categories. The results are indeed statistically different, at 1% significance level.

4.2. Analysis of shifts and rerouting

Table 1 describes departure and arrival shifts of the analysed scenarios, and is organised as follows. Column 1 indicates the scenario. Column 2 shows the number of flights shifted in time. Columns 3 and 4 show the values of average departure and arrival shifts per shifted flight, respectively. Values are given in minutes per shifted flight. Finally, columns 5 and 6 provide the average departure and arrival shifts calculated over all flights, expressed in minutes per flight. Note that BMD has no shift by definition and is therefore not included in the table. Similarly, BMC has no departure shift by definition.

Predictably, SMS is the solution scenario with the lowest number of shifted flights and, as a consequence, with the smallest average shifts over all flights. The SMC scenario reports a quantity of shifted flights that is more than twice the quantity of flights shifted in the SMS scenario. Notice that the percentage of flights shifted in time is low, as it is less than 4% of all flights. This indicates that to respect nominal capacities, a very small portion of flights needs to be shifted in time – by an average of around 4 min at departure and 4 min at arrival – thus having a small impact on strategic flight operations planning.

Fig. 4 shows the distribution of the number of flights shifted by a number of minutes in solution scenarios for departure and arrival shifts. The SMS scenario (see black lines) provides a lower number of shifted flights for each shift level, both at departure and arrival, in line with the lower total number of shifted flights reported in Table 1. For both SMS and SMC scenarios, most flights have small departure or arrival shifts, and very few report large shifts (there are less than 10 flights with a shift of 15 or more minutes, in both solution scenarios).

The analysis above shows that a very small portion of flights needs to be shifted (in time) to respect capacities. However, the shift is only one aspect of the decisions that can be made in the model. Choosing a different route is another option.

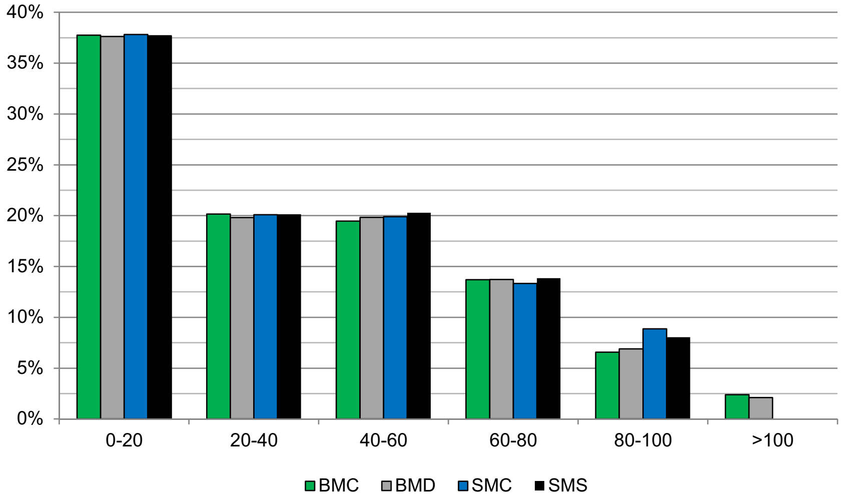

Fig. 2. Distribution of sector capacity utilisation across scenarios.

Table 2 shows the number of flights with a different route choice in the solution scenario with respect to the route choice of the baseline scenario. As can be seen, a fair portion of flights choose a different route: 30.59% in time-based scenarios (SMS vs BMD), and 19.12% in cost-based scenarios. At the same time, these route choices result in the departure or arrival time shift of less than 4% of flights, thus having a rather small impact on the schedule, while respecting the nominal capacities of different network elements.

Let us demonstrate the workings of the model on a couple of examples. The left panel of Fig. 5 shows the route choices for a flight between Vienna and Madrid in BMC and SMC scenarios. Total costs of the red[5] route chosen in BMC scenario are lower than those of the blue route (SMC). The red route passes through a congested sector in France (over 100% capacity utilisation), depicted by the green area. As in the BMC scenario the sector capacities are not enforced, the red route can be chosen, and it is the cheapest option in this scenario. On the contrary, in SMC the capacities are respected, thus shifting the flight to the blue route that is slightly more expensive overall (10,406.50 € *versus* 10,311.20 €), but with lower route charges (1,590.54 € *versus* 1,669.19 €), even though the blue route is 3 min longer. The right panel of Fig. 5 shows a slightly different example. Here, the flight between Enfidha-Hammamet and Prague airports is analysed. The red route is used in BMC, while the blue one is used in SMC scenario. The routes are of the same duration (i.e., 133 min), thus having the same operational costs. Route charges, and consequently total operational costs, are higher in SMC scenario as the blue route passes through the more expensive airspace. The more expensive route is chosen in SMC, as the cheaper route passes through the sector that is congested at the time the flight is expected to enter this airspace, thus making this choice impossible for the model.

4.3. Analysis of flight operational costs

We now compare the difference of costs between solution and baseline scenarios. First, we provide a breakdown of flight operational costs based on the source, i.e., airborne costs, fuel costs, ground holding costs, and route charges, across the different scenarios, see Table 3. As can be seen, the average airborne and fuel costs are almost the same across all four scenarios. The difference can be noted across average route charges. Route charges for BMC and SMC are about 25 € lower than those of BMD and SMS scenarios, which account for the difference between the total average costs across scenarios. This indicates that cost-based scenarios are able to avoid more expensive routes, leading to non-negligible monetary savings (around 3% of route charges costs on average). Further, it can be noted that the standard deviation of total costs is rather large, which is to be expected, as the flights' duration ranges from 10 to 15 min (local connections), to several hours (intercontinental flights).

Then, we evaluate the differences in decisions made across scenarios. More specifically, we compare the SMC to the BMC scenario, as they are cost-based, and the SMS scenario to the BMD scenario, as they are based on shift and duration. The evaluation of different flight plan choices between baseline and solution scenarios can be found in Table 4. The information in this table presents the average cost values, where the costs are averaged across the flights shifted in space and/or time, that is to say, where the flights have different flight plans. Negative differences indicate costs that are lower in the scenario solution than in the baseline solution.

The results obtained analysing the costs of the flights with different flight plans only show greater differences than what was seen over all flights. In the case of SMS *versus* BMD, 31.5% of flights change their flight plans, switching to slightly longer

[5] For interpretation of colour in Fig. 5, the reader is referred to the web version of this article.

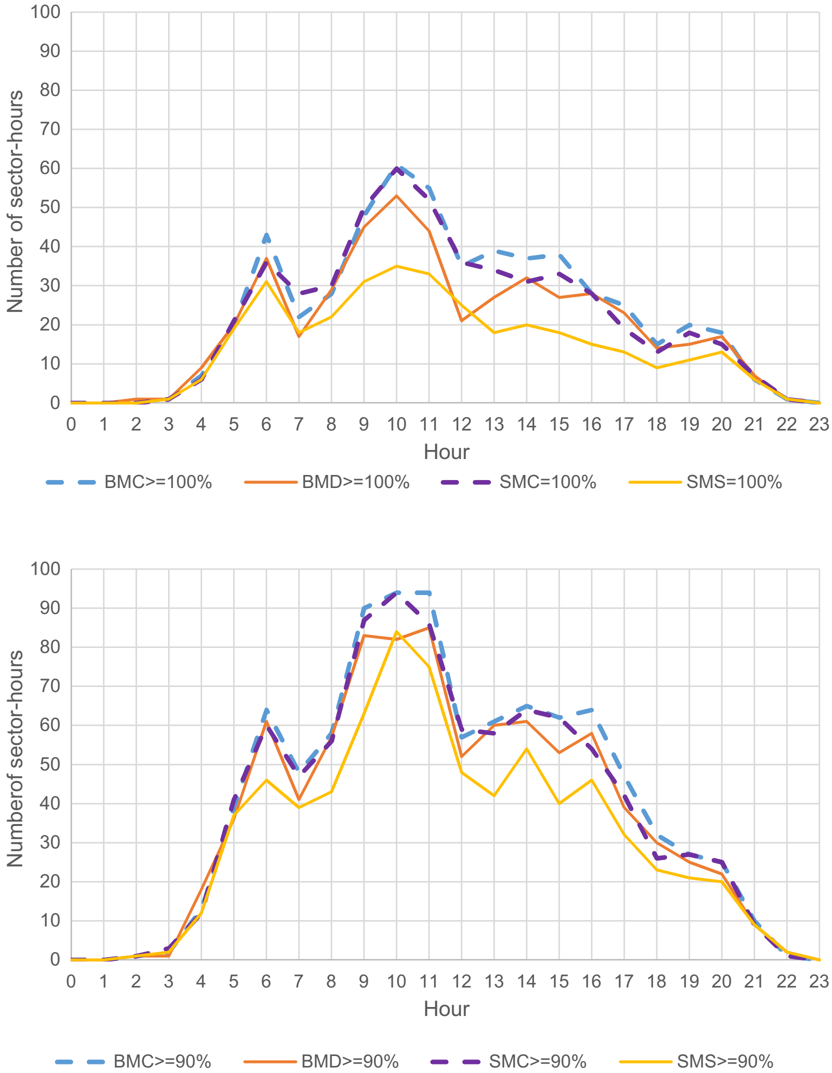

Fig. 3. Upper panel: distribution of sector-hours with capacity utilisation of 100% or more. Lower panel: distribution of sector-hours with capacity utilisation of 90% and more.

Table 1
Departure and arrival shifts, number of shifted flights.

Scenario	Shifted flights	Dep shift per shifted flight (min/shifted flight)	Arr shift per shifted flight (min/shifted flight)	Dep shift per flight (min/flight)	Arr shift per flight (min/flight)
BMC	195	N/A	2.04	N/A	0.01
SMS	482	3.99	3.99	0.07	0.07
SMC	1,129	3.78	4.20	0.15	0.16

routes (airborne and fuel costs are slightly higher), where the route charges are lower (−5.34 €). Thus, SMS scenario provides flight plan distribution that is cheaper for 1.85 €/flight with different flight plan. The number of different flight plans is lower in the SMC *versus* BMC case (21.6%). The results indicate that the flights switch to shorter duration routes (airborne and fuel costs are lower), which have higher route charges. Thus, the costs of different flight plans in case of SMC *versus* BMC are on average higher for 8.75 €/flight with the different flight plan.

These results show that the proposed flight plans have a modest impact on average strategic costs. On the other hand, they provide a better traffic distribution, since they respect the boundaries defined by the nominal capacities of sectors.

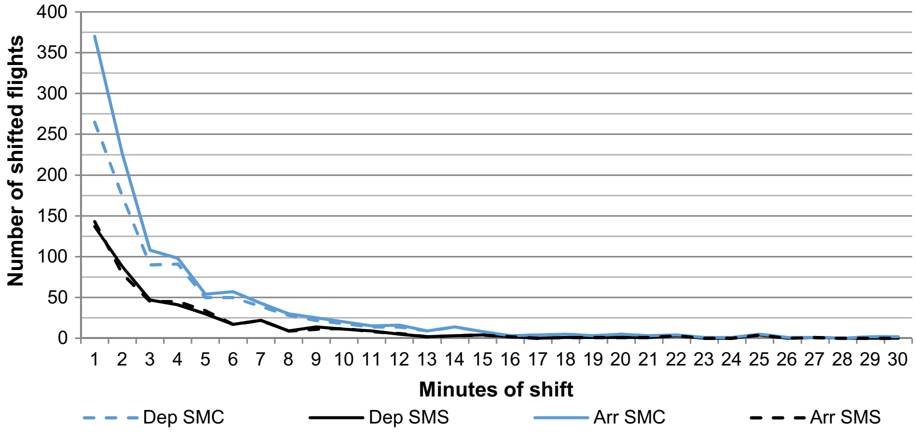

Fig. 4. Number of shifted flights at departure and arrival, for each value of shift, across different solution scenarios.

Table 2
Number of flights with different routes between baseline and solution scenarios.

	SMS vs BMD	SMC vs BMC
Number of flights with different routes	8,953	5,598
Percent of total flights	30.59%	19.12%

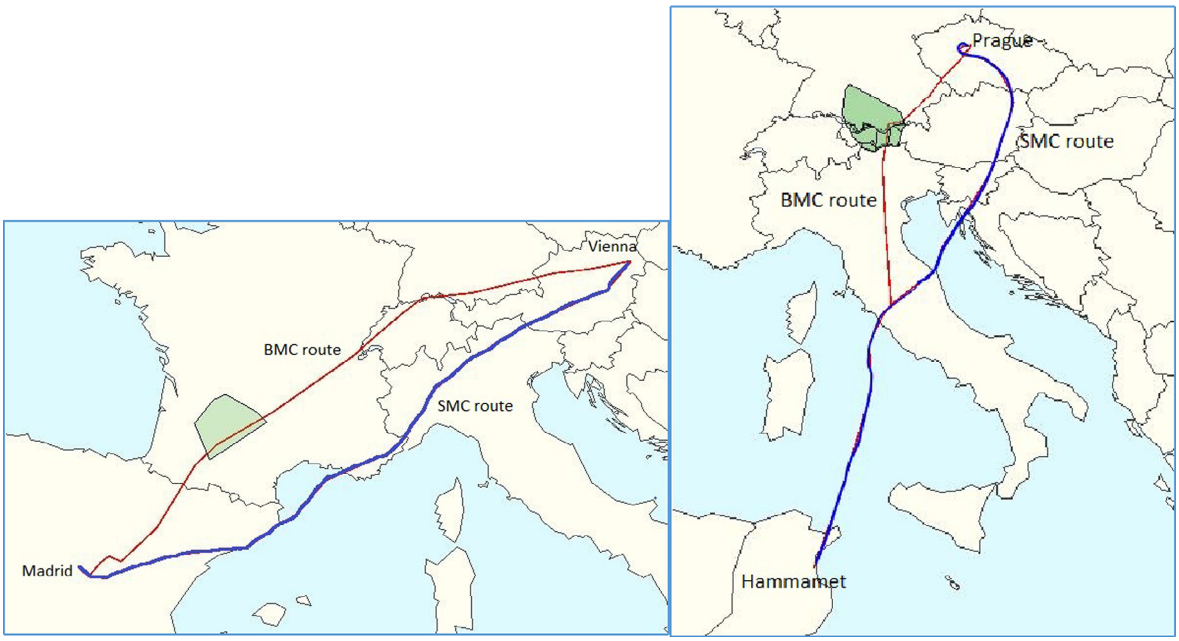

Fig. 5. Different route choices between BMC and SMC.

5. Results analysis: simulation and evaluation of the tactical impact

As mentioned in the Introduction, the usefulness of strategic traffic assignment holds as long as delays and associated costs for airlines in the *tactical phase* are likely to be reduced. While some delays are due to airline schedule disruption (e.g., aircraft repair), most of the tactical delays are due to the ATFM delays that are imposed by regulations. Each regulation is characterised by the start and end time, location, capacity to be applied and the underlying cause of the regulation. The regulation causes are divided in the following categories: aerodrome capacity, ATC capacity, ATC staffing, environmental issues, ATC equipment, ATC routing, weather, or other reasons. Currently, the regulations are applied on the day of

Table 3
Average strategic cost breakdown (€/flight).

	BMD	BMC	SMS	SMC
Airborne costs	3,498.28	3,498.69	3,498.43	3,498.62
Fuel costs	4,817.61	4,818.21	4,817.81	4,818.17
Ground costs	–	–	0.75	1.21
Route charges	736.74	710.86	735.06	711.64
Total cost	9,052.63	9,027.76	9,052.05	9,029.65
Std. dev.	17,302.47	17,236.17	17,292.93	17,236.27

Table 4
Variations in flight operational costs (€/flight with different flight plan).

	SMS vs BMD	SMC vs BMC
Different flight plans	9,226	6,331
Percent	31.5%	21.6%
Airborne costs (€)	0.47	−0.31
Fuel costs (€)	0.63	−0.17
Ground costs (€)	2.38	5.61
Route charges (€)	−5.34	3.60
Total cost	−1.85	8.75

operations, after coordination and agreement between the flow management position of an ANSP, and the Network Manager Operations Centre (NMOC), using the Computer-Assisted Slot Allocation (CASA) algorithm. CASA is largely automatic and centralised, applying the 'First Planned – First Served' principle. The algorithm first finds all the flights planned to enter affected sectors and sequences them in the order they would have arrived at the airspace in the absence of any restriction. Then, the algorithm assigns ATFM slots (ground delay) to the flights in excess of the regulation imposed capacity, and the new take-off time, the so-called Calculated Take-Off Time (CTOT), is communicated to the airline (EUROCONTROL, 2016). ATFM slots are assigned 2–3 h prior to the flight's departure time. During this time period airlines have a choice of accepting the assigned slots (i.e., delay) or rerouting their flight around the regulation, if that is possible. For example, in case the departure airport is under regulation, it would not be possible to reroute the flight. When rerouting is possible, in order to decide if and how to reroute the flight, the airline takes different factors in consideration, like aircraft payload at the moment and aircraft performance characteristics (e.g., ceiling, climb rate), punctuality requirements (e.g., is it a feeder flight?), crew requirements (e.g., time on duty), reactionary delay induced, just to mention some. Airlines weigh such factors in a different way, depending on the needs of the moment and/or their business model. As such information is not available to us, we focus on the tactical impact of the assignment of ATFM slots only, without taking rerouting into consideration. In the USA, some en-route regulations are termed Collaborative Trajectory Options Program (CTOP) (Federal Aviation Administration, 2014). The difference between European and USA ATFM management is that when the CTOP is active, flights are assigned one of the preferred routes and/or delay that an airline communicates to the Air Traffic Control System Command Center. Conversely, in Europe, the airlines can accept the assigned delay or try to re-route around the regulation.

In order to assess how the strategic traffic distribution would fare tactically, we simulate the application of regulations and related ATFM delays on the flight plans obtained from our baseline and solution scenarios. First, let us review the difference between the baseline and solution scenarios. In the baseline scenarios (BMD and BMC), the nominal capacities of network elements (i.e., airports and sectors) are not binding, thus mimicking the current situation where the airspace users file flight plans without the need to respect the capacity limits. The check on capacity limits arrives with the activation of regulations only. On the other hand, flight plans obtained from the solution scenarios (SMS and SMC) respect the nominal capacities of all elements of the network, i.e., there are no nominal capacity breaches as in the baseline scenarios. What we want to investigate is whether the strategic flight planning that respects the capacity of all network elements decreases the amount and cost of tactical delay. In other words, is the ATFM delay lower for flight schedules in solution scenarios when compared to baseline scenarios, when the same regulations are applied?

Second, let us turn to the simulation of ATFM delay assignment. At least one regulation has to be active in order to start the CASA algorithm that then assigns the ATFM delay to the flights in excess of capacity limit. In this simulation, the sectorisation and regulations that were in place on September 12th 2014 are used. All regulations except the ATC routing ones are taken into account. ATC routing regulations are excluded from the simulation as those practically close the affected airspace (i.e., capacity becomes 0). As mentioned above, in real life operations, the flights can be re-routed around such regulations. However, as our simulation does not take re-routing in consideration, the resulting ground delays would be vastly exaggerated, thus this category of regulations is excluded from the simulation.

Finally, to simulate the ATFM operations management, we use the ISA-CASA algorithm, a direct C++ translation of the CASA algorithm, available in the NEST modelling tool. The flight plans obtained from a scenario and the list of active regulations are loaded into the NEST modelling tool, and the ISA-CASA algorithm is run. The result of ISA-CASA is a list of flight plans where the flights affected by the regulations are delayed (CTOT is assigned). This process is applied for all baseline and solution scenarios (BMD, BMC, SMS, SMC).

To sum up, the main assumptions in the tactical impact analysis are the following:

1. Dynamic sectorisation is applied, the same one as in the model (as the sectorisation depends on the traffic volume and complexity).
2. There is no strategic shift of operations, the applied delays are tactical and the assigned costs are tactical (and thus superlinear).
3. The route cannot be changed (re-routing is not simulated). Only delay can be assigned.
4. Regulations are applied, and the regulation capacities are always enforced.

5.1. Strategic assignment's impact on tactical delays

The results of the application of the ISA-CASA algorithm on flight plans from baseline (mimicking the current situation) and solution (strategic planning) scenarios are illustrated in Table 5.

Results show a tangible decrease of ATFM delays in solution scenarios, when compared with baseline scenarios' delays. Making time-based decisions (SMS vs BMD), our strategic model decreases delays by 8.9%. Making cost-based decisions (SMC vs BMC), our model decreases delays by 8.6%. The number of flights affected by delays is also lower, as it decreases from 917 and 956 flights in baseline scenarios down to 826 and 886 flights in solution scenarios, respectively. The average delay per delayed flight, on the other hand, is quite similar across the four considered scenarios. To sum up, both the amount of delay and the number of delayed flights are lower for flight plans from solution scenarios with respect to baseline scenarios.

Further, we analyse the distribution of delay across the regulation causes. As mentioned above, there are different categories of regulations that are further divided according to the place of application, which could be: area control centres (ACCs), airports, navigation points, and sectors. As our approach respects nominal sector capacities in the strategic phase, we are interested in analysing the variation of delays due to en-route ATC capacity regulations (i.e., at sectors, navigation points and ACCs) across baseline and solution scenarios. The results are shown in Table 6.

In time-based scenarios (BMD vs SMS), the en-route ATC capacity delays decrease by 25.3%. In cost-based scenarios (BMC vs SMC), the improvement is even larger, and amounts to 28.6%. As the major share of en-route ATFM delay on annual level is due to the ATC capacity regulations (i.e., 46% in both 2014 and 2015), the decrease of about 25–29% is not negligible. To put it in perspective, in 2014 en route ATC capacity delay amounted to 2.7 million minutes of delay (EUROCONTROL, 2015).

5.2. Strategic assignment's impact on tactical costs

Delays do not only have an impact on time, but also on costs, as they can be expensive for airlines. Thus, we also analyse the cost of tactical delay. So far, our strategic models used the strategic costs to calculate flight operational costs. Strategic costs are those that can be accounted for in advance, and do not take into account unforeseen perturbations, nor the passenger costs. Tactical delay costs arise from unplanned delays on the day of operations. It is important to note that tactical costs are a superlinear function of delay, i.e., a minute of delay costs more the longer the delay is. In this analysis, we use the cost of delay values published by Cook and Tanner (2015). They divide the tactical delay in the following categories: at-gate, taxi, en-route and arrival delay. Since in our simulation only ground delay is possible (i.e., no re-routing), which is usually taken at the gate, only Cook and Tanner's at-gate tactical costs are applied (see Tables 26, G1 and G2 from their report).

At-gate tactical costs include the maintenance, crew, and passenger costs per minute. For example, crew costs include overtime pay. Passenger costs are formed by "hard" and "soft" costs. "Hard" costs are due to factors such as rebooking, compensation, and care. "Soft" costs consider the loss of market share due to unpunctuality. Due to their nature, passenger costs are a superlinear function of delay, thus making the tactical costs superlinear. In Cook and Tanner (2015), passenger per-minute costs (and consequently total at gate tactical costs) are given for delay durations of 5, 15, 30, 60, 90, 120, 180, 240, and 300 min. Listed costs are used when delay matches given durations, and linear interpolation of costs when a delay falls within two given delay durations. The evaluation of tactical delay costs is shown in Table 7.

Results show that total delay costs are lower in solution scenarios, as the amount of delay is lower. For time-based scenarios (BMD vs SMS), the reduction is 10.5%. For cost-based scenarios (BMC vs SMC), the cost reduction is 10.9%. Further, let us compare strategic and tactical costs of flights affected by ATFM regulations, across our four scenarios: two where the decisions are time-based and two that are cost-based. As seen above, the number of delayed flights changes across scenarios. In order to make this comparison sensible, the flights that are delayed in each of the paired scenarios (time-based, cost-based) first need to be identified. A set of flights for the time-based scenarios comparison is obtained by the union of the flights delayed in BMD and flights delayed in SMS scenarios. From 917 and 826 flights delayed in the BMD and SMS scenarios, a total of 939 different flights are identified. Some of these flights are delayed only in BMD scenarios, some only in SMS scenario, and some (most) are delayed in both scenarios. Similarly, there are 986 different delayed flights between BMC and SMC scenarios. Average strategic and tactical costs are reported for these flights only, see Table 8.

Table 5
Tactical delay simulation results across different scenarios.

Instance	Delay			Delayed flights	Del. per delayed flight (min/delayed flight)
	Total (min)	vs BMD (%)	vs BMC (%)		
BMD	13,137	N/A	−3.3	917	14.33
BMC	13,577	+3.2	N/A	956	14.20
SMS	12,060	−8.9	−12.6	826	14.60
SMC	12,503	−5.1	−8.6	886	14.11

Table 6
Variation of delays due to en-route ATC capacity regulations.

Scenario	Delay (min)
BMD	1,028
BMC	1,649
SMS	768
SMC	1,177

Table 7
Tactical delay costs.

Scenario	Total delay cost (€)	Average cost (€/delayed flight)	Per-minute delay cost (€/min of delay)	Total vs BMC (%)	Total vs BMD (%)
BMD	638,675.60	696.48	48.62	−1.8	N/A
BMC	650,182.67	680.11	47.89	N/A	1.8
SMS	578,241.73	700.05	47.95	−12.4	−10.5
SMC	586,468.50	661.93	46.91	−10.9	−8.9

Table 8
Average flight costs for tactically delayed flights (€/delayed flight).

Scenario	Time-based scenarios			Cost-based scenarios		
	BMD		SMS	BMC		SMC
Flights		939			986	
Strategic cost (€/d.flight)	7,504.36		7,511.62	8,894.70		8,900.64
Difference (€/d.flight)		7.26			5.95	
Cost of tactical delay (€/d.flight)	680.17		615.81	659.41		594.80
Difference (€/d.flight)		−64.36			−64.62	

First note that the average strategic costs of flights delayed in time-based scenarios are significantly lower from those in cost-based scenarios. Total average strategic costs of time-based scenarios (see Table 3) are higher than those of the cost-based scenarios. Thus, having the strategic costs of time-based scenarios higher in this analysis, indicates that these two sets of flights are different, cost-based scenarios set being composed of on average longer flights. The difference between the strategic costs in time-based scenarios is 7.26 €, and 5.95 € in cost-based scenarios, indicating that the cost of traffic redistribution from baseline (be it time or cost based) to respect the capacity in solution scenarios is rather low. However, this small strategic investment enables the savings of 64 €, on average, for delayed flights in both solution scenarios. Thus, slightly higher strategic costs (less than 0.1%) for flying along the routes that respect the network capacities, result in lowering the average costs of tactical delay for 64 €/delayed flight (in both time and cost based cases). In 2014, ATFM delay was assigned to 532,598 flights in Europe. If the cost of delay can be lowered by 64 € for each flight, in 2014 that would have enabled savings of about 34 million € yearly. Thus, the little investment in strategic flight planning is worth paying for.

Furthermore, Table 6 of Section 5.1 shows that solution scenarios traffic assignment lowers for 25–29% the amount of delay due to ATC capacity regulations. As previously mentioned, the en route ATC capacity regulations accounted for 2.7 million minutes of delay in 2014. If by using strategic flight planning this amount of delay could be decreased by 20%, to be on a conservative side, this would result in about 26 million € of savings (using the most conservative average costs reported in Table 7).

6. Conclusions

In this paper, we evaluate the benefits of an early flight planning in terms of reduction of delays and their associated costs. The proposed model is a new contribution to literature on air traffic as it specifically addresses strategic flight planning, while the ATFM models to date address tactical problems. The main contribution lies in the combination of tackling *large-scale* strategic flight planning *using hard capacity constraints* (i.e., ensuring that nominal capacities are respected), while considering the *whole network* (i.e., both airports and sectors), and using the *real historic data* for network and traffic description. The model is able to manage the dynamic evolution of the configuration of the airspace throughout a day. Moreover, it is able to accurately represent the flight times of different routes through a single sector. These characteristics make it directly applicable to real flight data, thus increasing the possibility of actual implementation in ATM.

The model can be run with minimum shift (MS) or minimum cost (MC) objective functions, using estimated actual operational costs for all flights. In both objective functions, superlinearity is used to achieve equity, as proposed by Lulli and Odoni (2007). An in-depth analysis of the solution obtained on one instance of real traffic data taken from September 12th 2014, the fourth busiest day of 2014, is presented. The computational time required to solve this instance is around 4–5 min for both the MC and MS objective functions; such computation times, in the strategic phase (months before the operation of flights), are more than acceptable. For illustration purposes, the run time required for the model by Bertsimas et al. (2011) is on the order of 10–15 min, for a significantly smaller, albeit more complex problem.

The results show that in both *solution* scenarios flights are redistributed, with respect to the *baseline* scenarios: about 30% for SMS and 19% for SMC flights. SMS results in smaller overall shift, both in terms of amount of shift and the number of shifted flights, but in higher route charges, resulting in higher total flight costs. Outcomes of SMC have higher values of shift (and number of shifted flights), but lower route charges, resulting in lower total costs. The goal of both solution scenarios is to redistribute flights so that airspace and airport capacities are respected. With that in mind, it is interesting to note that in our experiments, even though a substantial portion of flights chooses different routes, only a relatively small percentage needs to be shifted in time (less than 4%) to achieve this goal, at this level of traffic demand. As congestion is a localised phenomenon, reroutes inevitably increase traffic load in surrounding areas, but keep the number of flights planned to enter sectors below or at nominal capacity.

As the usefulness of strategic traffic assignment holds as long as delays and associated costs for airlines in the *tactical phase* are likely to be reduced, we simulate delays using the ISA-CASA algorithm and apply regulations that were in place on the considered day. Results show a decrease in the number of delayed flights of about 10% for both SMS and SMC, compared to the respective baselines. In particular, a reduction of around 30% of delays due to ATC capacity regulations is reported. The impact of delay reduction on costs is also evaluated. Results show that delay costs are lowered on average by 64 €/delayed flight in solution scenarios. In 2014, that would have enabled savings of about 34 million € in Europe (for 532,598 delayed flights in the European airspace). It should be kept in mind that the tactical impact analysis does not take into account the re-routings, so the results are probably on the conservative side.

A direct comparison of results from other studies is not possible due to the novel nature of our approach, which applies an optimisation model for a whole air traffic network with strict capacity constraints to a strategic problem for the first time. However, other publications, such as the one by Jacquillat and Odoni (2015), also support the validity of strategic planning as a means to reduce ATFM delay.

The model in its current form clearly has some limitations. Firstly, it assumes a fully deterministic context, while strategic planning, taking place months in advance of the day of operations, should take some uncertainty factors into account. Secondly, it ensures fairness at a flight level, but does not guarantee fairness towards airlines. Furthermore, the experiments presented here take into account only one day. Nevertheless, the data are taken from the fourth busiest day of 2014, selected as not unduly disrupted by unusual events (e.g., strikes, extreme weather conditions), as these events cannot be foreseen strategically. The model demonstrates that it can deal with the amount of traffic and complexities (e.g., sectorisation) of a busy day. On the other hand, the analysis of the tactical impact would benefit from the inclusion of a wider variety of regulations in the tactical delay simulations, containing extreme weather and other events, at different places in the network. Such extended analysis would offer a much better picture of the tactical impact of strategic planning, and most likely indicate the uncertainty factors to include in the stochastic extension of the model. Such aspects shall be investigated in future, as the results obtained from this first study are encouraging.

The concept of strategic flight planning (submission of flight plans months in advance of the day of operations) is supported by the fact that the European ATM Master Plan foresees as the cornerstone of the future ATM system the early sharing of information from all stakeholders. Nowadays, flight planning data are collected by the Network Manager that then centrally manages agreed ATFM measures tactically. In a possible implementation of strategic planning we assume that airlines would submit flight plans comprising of the main route and preferred alternative routes (e.g., a CTOP-like scheme), thus informing the CP of their preferences.

We believe that strategic flight planning could bring along an acceptable compromise between flexibility and predictability. This represents a key issue in the current European ATM system, where a significant tactical-strategic gap exists between the operations planning horizons of airlines and ANSPs: the past 20 years saw the move towards tactical planning, thus providing airlines with more flexibility. In order to be economically efficient, airlines exploit the possibility to plan the actual routes on the day of operations as then all the data that influence the particular flight are known. ANSPs, on the other hand, would like to receive information 12 months ahead of flights in order to be able to effectively plan the air traffic controllers' rosters and the airspace opening schemes. Despite this gap, the common agreement is that predictability is something all the stakeholders wish (SATURN, 2015), which strategic flight planning could bring along. Predictions and forecasts are not and will not be perfect, so flexibility will still be needed. As long as strategic planning allows for tactical flexibility, like the continued application of the current ATFM management, we believe it might be acceptable to airlines. The results presented in this paper indicate that strategic planning can be economically viable. Thus, we think that this is definitely a subject worth further investigation.

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Glossary

Term: Definition
ACC: Area Control Centre
ANSP: Air Navigation Service Provider
ATC: Air Traffic Control
ATFM: Air Traffic Flow Management
ATM: Air Traffic Management
BMC: Baseline Minimum Cost
BMD: Baseline Minimum Distance
CASA: Computer-Assisted Slot Allocation

CP: Central Planner
CTOT: Calculated Take-Off Time
DDR: Demand Data Repository
ECAC: European Civil Aviation Conference
FSC: Full-Service Carrier
IATA: International Air Transport Association
LCC: Low-Cost Carrier
MC: Minimum Cost
MS: Minimum Shift
MTOW: Maximum Take-Off Weight
NEST: Network Strategic Tool
NMOC: Network Manager Operations Centre
OD: Origin-Destination
SMC: Solution Minimum Cost
SMS: Solution Minimum Shift