EXPLORATORY RESEARCH

D3.1 Flight flexibility and hotspots in the ADAPT solution

Deliverable 3.1

ADAPT

Grant:	**783264**
Call:	**H2020-SESAR-2016-2**
Topic:	**SESAR-ER3-03-2016 Optimised ATM Network Services: TBO**
Consortium coordinator:	**Università degli Studi di Trieste**
Edition date:	**28 February 2019**
Edition:	**01.01.00**

Founding Members

EUROPEAN UNION EUROCONTROL

SESAR JOINT UNDERTAKING

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Document History

Edition	Date	Status	Author	Justification
01.00.00	21 December 2018	Release	ADAPT Consortium	New document for review by SJU
01.01.00	28 February 2019	Release	ADAPT Consortium	Review comments addressed

ADAPT

ADVANCED PREDICTION MODELS FOR FLEXIBLE TRAJECTORY BASED OPERATIONS

This deliverable is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 783264 under European Union's Horizon 2020 research and innovation programme.

Abstract

This deliverable reports the formulation and implementation of a deterministic model (European Strategic Flight Planning (ESFP) model) to define flight trajectories and associated time windows at the strategic level.

The EFPS model assigns the trajectory, departure time and flexibility measure for all the flights in the data instance (the ECAC network for the entire day of traffic). Apart from that, for each constrained flight the limiting sector-hour is identified, which can be of help in case the airline user would prefer to re-route the flight in order to increase its flexibility.

Furthermore, the model gives the list of saturated sector-hours throughout the day. Keep in mind that the configurations are changed during the day. Having the information on the saturated sectors, and their criticality index, the ANSPs could take mitigation actions in order to improve the situation. For example, a supervisor having one or two saturated sectors, both with the low criticality index, might decide that the current configuration is good enough as even if the capacity ends up being violated it will be for a small number of flights, which in many cases is what already happens in every-day operations. However, if there are few sector-hours within an ACC that have high criticality indexes, the supervisor might decide to change the configuration into a one that brings more capacity.

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Executive summary

The goal of the ADAPT strategic solution is to enhance the early flight planning, giving an indication of how critical or flexible the execution of each flight can expect to be, and to indicate to which extent the nominal capacity of each element of the network (i.e., sectors and airports) is going to be respected.

The first phase of the development of the ADAPT solution, which is the formulation and implementation of a deterministic model (European Strategic Flight Planning (ESFP) model) to define flight trajectories and associated time windows at the strategic level, is presented in this deliverable. The ESFP model builds on two deterministic, integer programming models. The first model, that we term Strategic Air Traffic Assignment (SATA) model, was developed in the SATURN project, and its aim is to assign a trajectory for each scheduled flight, in such a way that the nominal capacities of the network are respected. When all flights have a trajectory and departure time assigned, these become inputs of a second integer programming model, called Time Window (TW) model. This model uses departure times as the starting position of each TW, and the objective is to guarantee the largest flexibility by maximising the total duration of all TWs, i.e., the sum of the duration of all individual TWs. The output of this second model are the trajectories, assigned TWs and the hotspots (saturated elements) in the network.

Here we present the three variants of the TW model, which differ in the approach to accounting capacity:

1. Conservative, reserves a unit of capacity for any sector-hour the TW extends over, even though the flight will use only one unit of capacity in either of the two sector-hours.
2. Proportional model, a fraction of unit of capacity is assigned to each period of TW duration, where the fraction is obtained by dividing the unit of capacity by the number of periods in the TW (duration).
3. Intermediate, reserves the whole unit of capacity for the portion of the TW duration that falls within the first sector-hour, and a fraction of the unit of capacity for all the remaining periods of the TW that fall within the second sector-hour.

The EFPS model is run on a day of real air traffic data, encompassing the entire European Civil Aviation Conference airspace. Different data items are needed to run the SATA and TW 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), for September 12th 2014. Cost data are taken from the report by (Cook & Tanner, 2015). In this deliverable we focus on the results of the TW model. However, it is important to keep in mind that the SATA model is the input of the TW model, thus the TW model results reflect the results of the SATA model as well.

The results show that the three TW models perform differently, proportional model being the one that identifies the lowest number of constrained flights (those with TW lower than the TW_{max}), followed by the intermediate model and closing with the conservative one. However, the proportional TW model is also the slowest, and according to the outputs of the feasibility analysis could result in the highest number of capacity violations. The results also change with the chosen TW duration – the longer is the TW, more flights are identified as constrained.

Based on the results, the intermediate TW model is the preferred TW model: it reserves the capacity in a less constraining manner than the conservative model, and results in less capacity violations than the proportional TW model. We tested different TW durations – 10, 15 or 20 minutes. It is our opinion that the TW of 15 minutes is most useful, as it requires less of unnecessary capacity reservations, and is of the same length as the ATFM slots. However, as both the minimum and maximum durations of TWs are the parameters of the model, they can always be changed.

The EFPS model assigns the trajectory, departure time and flexibility measure (TW) for all the flights in the data instance (the ECAC network for the entire day of traffic). Apart from that, for each constrained flight the limiting sector-hour is identified, which can be of help in case the airline user would prefer to re-route the flight in order to increase its flexibility.

Furthermore, the TW model gives the list of saturated sector-hours throughout the day. Keep in mind that the configurations are changed during the day. Having the information on the saturated sectors, and their criticality index, the ANSPs could take mitigation actions in order to improve the situation. For example, a supervisor having one or two saturated sectors, both with the low criticality index, might decide that the current configuration is good enough as even if the capacity ends up being violated it will be for a small number of flights, which in many cases is what already happens in every-day operations. However, if there are few sector-hours within an ACC that have high criticality indexes, the supervisor might decide to change the configuration into a one that brings more capacity.

As EFPS model is aimed at the strategic/pre-tactical flight planning phase, it can be used in the further analysis of the system performance by different stakeholders – airlines, ANSPs, airports and Network Manager. As the models are fast, they could also be used in the what-if scenarios, for example re-routing or change of configuration.

It is important to note that even in the worst case (conservative TW model, TW of 20 minutes), about 25% of total daily flights are identified as constrained, out of which only a small portion (less than 3% of total daily flights) are heavily constrained (TW of 1 minute). Most of other flights identified as constrained still have some flexibility, and what is more, this flexibility is quantified – each flight is assigned a TW of a certain duration.

Apart from the number of constrained flights, and their flexibility (assigned TW), TW models can identify which are the network elements that impose limits on the flight's flexibility, which can be useful to airlines as well as to the air traffic control.

1 Introduction

The goal of the ADAPT strategic solution is to enhance the early flight planning, giving an indication of how critical or flexible the execution of each flight can expect to be, and to indicate to which extent the nominal capacity of each element of the network (i.e., sectors and airports) is going to be respected.

The ADAPT project consists of:

1. Development of the ADAPT strategic solution.
2. Tactical assessment.
3. Visualisation.

The development of the ADAPT strategic solution consists of three phases:

1. the formulation and implementation of a deterministic model (European Strategic Flight Planning (ESFP) model) to define flight trajectories and associated time windows at the strategic level,
2. the assessment of the expected economic loss in case unwanted events occurring (e.g., flight delays, bad weather), and
3. the definition of some actions to mitigate on the day of operations expected demand and capacity imbalances, as detected in the two previous phases.

Phases 1 and 2 cover the definition of the ADAPT solution, while in phase 3 the outputs are used to devise mitigation actions in order to improve the situation, if possible.

In this deliverable, phase 1 of the development of ADAPT strategic solution, the initial computational experiments and obtained results are described. Phases 2 and 3 will be described, and their results presented in D3.2, due in month 18 of the project.

The European Strategic Flight Planning (ESFP) model builds on two deterministic, integer programming models. The first model, that we term Strategic Air Traffic Assignment (SATA) model, was developed in the SATURN project (Bolic, et al., 2017) and was used in the extensive computational experiments, taking into account a busy day in the European network, and the changing sectorisation. The aim of this model is to assign a trajectory for each scheduled flight, in such a way that the nominal capacities of the network are respected. When all flights have a trajectory and departure time assigned, these become inputs of a second integer programming model, called Time Window (TW) model. This model uses departure times as the starting position of each TW[1], and the objective is to guarantee the largest flexibility by maximising the total duration of all TWs, i.e., the sum of the duration of all individual TWs. The output of this second model are the trajectories, assigned TWs and the hotspots (saturated elements) in the network.

1.1 Introducing Time Windows (TW)

To reconcile predictability with flexibility, we propose to express the flight flexibility in terms of time windows, which are defined as time intervals associated with each flight segment (departure, arrival or entry into a sector) - as depicted in Figure 1.

Figure 1. Example of a trajectory and its sequence of time windows, red lines representing the shortest time windows.

A TW is characterised by its position (opening time) and duration (equal to closing time - opening time). In the context of strategic planning, the initial position of the time windows at departure and arrival could coincide with the corresponding scheduled departure and arrival times, which are available months before the actual day of operations. Scheduled times, however, are currently determined without considering airspace capacities. In order to take the capacities into account, and determine the time windows for flights, two steps, each corresponding to one of the two models, are taken.

First, the Strategic Air Traffic Assignment (SATA) model is applied, taking the changing sectorisations and associated capacities into account, and proposes possibly needed shifts (within a predefined threshold to comply with airport capacities and airspace users' business requirements) or alternative routes to meet them. A shift refers to moving the scheduled take-off or landing time to a time before or after the scheduled one. In particular, this first model identifies, strategically, take-off and landing times, and trajectories that minimise either the total shift or operational costs across all flights. Take-

[1] A time window is a time interval describing the flexibility (in time dimension) of a trajectory. A time window indicates how "late" (with respect to declared timing of the trajectory) a flight can be and still not create capacity-demand imbalances in the network.

off time and trajectory information enable determining the times of entry into sectors along the trajectory and finally the landing time. Thus, the opening time of each time window is set equal to the corresponding take-off time, landing time or entry into a sector as computed in the Strategic Air Traffic Assignment model. If each flight is operated so as to start the flight segments at the opening times of the associated time windows, all airport and sector capacities are met, and the minimum total shift (or operational costs) is achieved. In To grant the required flexibility, a flight might also be allowed to start the flight segments after the assigned, precise times. In order to evaluate how much later these actions can be performed, we use the TW model.

Thus, in the second step, the TW model is applied, giving as a result the duration of the time windows for each flight. The TW model maximises the total duration of all TWs, thus looking for the maximum flexibility for the flights in the system.

1.2 Introducing capacity matters

Current European ATM system offers a high level of flight planning flexibility, as only the final flight plans need to be submitted several hours before departure. On the one hand, this allows airspace users (AUs) the possibility to account for previously uncertain factors like weather forecasts, and thus create flight plans that are most convenient for the day of operations. On the other hand, this flexibility makes ATM system less predictable, resulting in costs due to flow measures, and under-utilisations from a mismatch between available ATM capacity and traffic demand. The available ATM capacity on the day of operations is often limited by the availability of the air traffic controllers.

When creating and subsequently submitting an initial flight plan, the airlines do not have the information on airspace nominal capacities and do not need to consider it. Thus, a precise traffic load on the airspace network is only known on the day of operations, while the capacity provision (e.g. staffing levels) is usually planned starting more than a year ahead and is updated as time progresses. On the day of operations in cases when available airspace (and airport) capacity cannot accommodate planned air traffic, the ANSPs and Network Manager agree on the Air Traffic Flow Management (ATFM) measures to reduce the demand on the congested parts of the network. The ATFM measures impose delays on flights crossing congested network volumes (AUs can re-route around the area in question). These delays and deviations are very costly to airlines (e.g. estimated to be more than 1B euro in 2014 (EUROCONTROL, 2017)).

Today, the airspace users do not need to consider the capacity of the airspace they would like to fly through. However, the European ANSPs have the information on what is considered the nominal capacity of each of the sectors under their jurisdiction. The actual capacity of an ANSP at each point in time depends on the applied sectorisation. Figure 2 depicts two configurations[2] of an ANSP: with just one sector (left figure), and with two sectors, where the division is in the horizontal plane (right figure). The nominal capacity of the first configuration is lower than that of the second one (42 compared to 95 entries in an hour).

[2] Configuration is a specific sectorisation. Airspace of each ANSP is divided in a number of elementary sectors. There are different combinations of these elementary sectors – configurations that can be used in operations.

European definition of a capacity is the number of entries within the defined time horizon, usually an hour. Thus, the nominal capacity defines how many flights can enter a sector during an hour, in nominal conditions. The weather conditions can require effective lowering of the nominal capacity, but that is done operationally, if there is a need for such measures (ATFM measures).

As the ADAPT models aim at the strategic/pre-tactical planning, hourly capacities are chosen, as they are deemed detailed enough at this planning horizon. In the tactical setting, the hourly capacity is usually considered too coarse and twenty-minute capacity is usually preferred. The EFPS model can use either 60 or 20-minute capacities, and is already doing so in some cases as explained in the following paragraphs. . However, focusing strictly on 20-minute capacities would increase the number of constraints, which is already high, and may or may not translate into longer computational times. More importantly, as the ADAPT is focused on improving strategic/pre-tactical planning, the 60-minute capacities are considered to be good enough. Keep in mind that in the current strategic setting the capacity figures are used very little by the ANSPs (when planning the traffic load, based on the historic data), and not at all by the airlines.

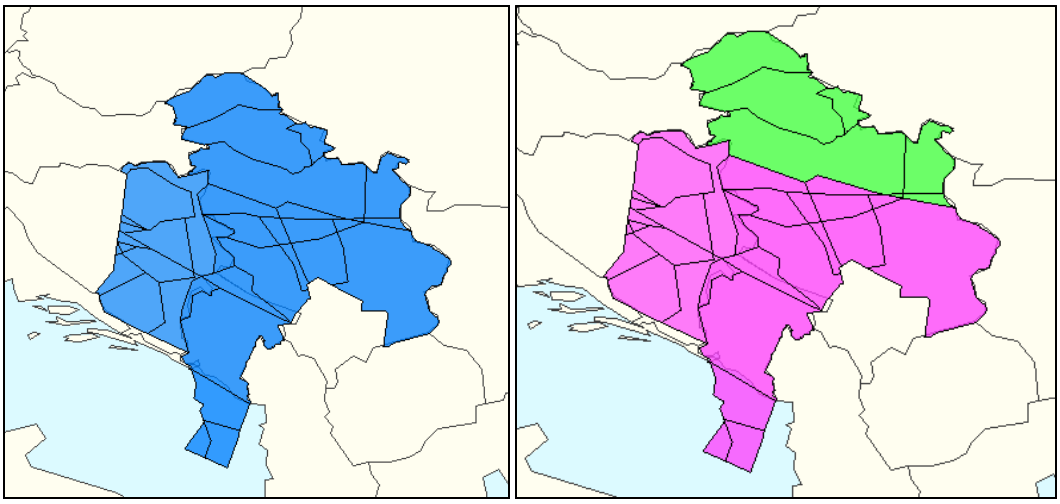

Figure 2. Sectorisation configurations with one active sector (left) and two active sectors (right).

The actual sectorisation is chosen by the supervisor based on the traffic demand prediction (short-term prediction based on the submitted flight plans) and the staff availability. The changes are actuated when the need arises, at any time of day.

Both optimisation models that are forming the ESFP model are formulated to include the capacity constraints. As the most frequent capacity definition used is the hourly one, in our models we use sector-hour capacity: hourly number of entries in the sector, when that particular sector is active. A sector is active, when the configuration it belongs to is active.

As the configuration changes at need, the change can happen at any fraction of an hour. For example, it can happen that a particular configuration is active from 8:00 to 10:20. In that case, the sectors belonging to that configuration would have three sector-hour capacities assigned – two full sector-hour capacities (from 08:00 to 10:00) and a partial sector-hour capacity where the hourly capacity is scaled to 20 minutes.

Furthermore, the ESFP models use the airport capacities as well. The airport capacities can be defined for arrival, departure or general (mix of arrival and departure) operations. Here the capacity is given as a number of such operations within a time period, usually an hour. For the sake of simplicity, we often refer to these airport-hour capacities as sector-hour capacities.

2 EFPS Model

In this section the mathematical formulation of the two EFPS models (SATA and TW) is given. Both models are centralised, meaning that all the needed information is collected in one place and the system optimum is sought.

2.1 SATA - Strategic Air Traffic Assignment

The goal of SATA model is to re-distribute traffic demand in such a way that the nominal declared capacities of network elements are respected. This model has been developed in the SATURN project and its formulation and computational experiments are described in (Bolic, et al., 2017). This model is a starting point of the EFPS model, and it is important the reader understands this first step, as it leads to the second, Time Window model. Thus, in order to have formulations of both of the EFPS models, we repeat the formulation of the model, as given in (Bolic, et al., 2017)

The SATA model has 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. Thus, the assumption is that shifts assigned so much in advance would not impact the tail-number dependencies. However, the model specification includes the tail-number dependency constraint, which are not applied as we do not have access to the tail number data[3].
- **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

[3] The additional notation and the tail-number dependency constraint for SATA model are given in the Appendix A.

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 , are defined, limiting the number of corresponding actions within a given time horizon (typically one hour). The same applies to sectors, where capacity limits the number of possible entries in a time horizon, following the European definition of sector capacity.

2.1.1 Notation for SATA model

The notation is the following:

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*
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 $f \in F$ and element index $i \in [1, n_r]$. This is different from the formulation commonly adopted in ATFM models, where trajectories are identified in terms of flight *f* and airport/sector $j \in S \cup K$ only (see for example Bertsimas *et al.*, 2011).

2.1.2 Decision variables

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

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

The decision variables represent the assignment, as allocated by the central planner, 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.

2.1.3 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.

2.1.3.1 Shift-based objective function

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:

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

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.

2.1.3.2 Cost-based objective function

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 & Tanner, 2015).

- Strategic ground costs are calculated as the unit ground cost (cg_a : cost of one minute 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 one minute 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:

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

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:

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

2.1.4 Constraints

The SATA model has the following constraints:

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

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

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

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

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

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

Constraints (5), (6), and (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, equations (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.

2.2 Time Windows model

The Time Windows is based on the same characteristics as the SATA model (see section 2.1)[4].

2.2.1 Notation

The notation used to define the model is the following:

A $\equiv$ set of airports, indexed by a,

S $\equiv$ set of sectors, indexed by s,

J $\equiv$ $A \cup S$ set of airports, and sectors, indexed by j,

F $\equiv$ set of flights, indexed by ,

$orig_f$ $\equiv$ departure airport of flight f,

$dest_f$ $\equiv$ destination airport of flight f,

R $\equiv$ set of routes, indexed by r, where r_f is a chosen route for a flight f,

n_f $\equiv$ number of elements (airports and sectors) along the chosen route r_f,

s_r^i $\equiv$ i-th element of the route r,

l_r^i $\equiv$ flight time from origin to the i -th element of route r,

d_f $\equiv$ scheduled departure time of flight f, i.e. the position of the departure TW,

w_{min} $\equiv$ minimum duration of each TW,

w_{max} $\equiv$ maximum duration of each TW,

$T_f^i \equiv \left\{d_f + l_{r_f}^1, \dots, d_f + l_{r_f}^i + w_{max} - 1\right\}$

$\equiv$ set of feasible time periods for flight f, to arrive at the i-th element of the route r_f,

$B \equiv \{dep, arr, gen, ent\}$

$\equiv$ set of actions that can be performed by a flight, dep, arr, gen stand for arrival, departure or generic movement type at an airport, and ent stands for entry into a sector,

C_j^b $\equiv$ set of sector-hours linked with the action b at sector or airport j, indexed by c,

$open_c$ $\equiv$ opening time period of sector-hour c, (i.e. opening time of a sector j),

$close_c$ $\equiv$ closing time period of sector-hour c,

$T_c \equiv \{open_c, \dots, close_c - 1\}$

$\equiv$ set of time periods during which the sector-hour c is active,

[4] TW model formulation includes the turnaround (tail-number dependency) constraints, as the SATA model, and those are given in the Appendix A.

Q_c ≡ capacity enforced during sector-hour c, (i.e. declared capacity of a sector j, during the sector-hour c)

2.2.2 Decision variables

Decision variables are used to capture the duration of departure Time Window for each flight:

$$x_f\ (t) = \begin{cases} 1, & \text{if the TW for flight } f \text{ is still open for departure at time } t; \\ 0, & \text{otherwise.} \end{cases} \qquad \forall f \in F, t \in T_f^0 \tag{11}$$

2.2.3 Objective function

The objective function maximises the total duration of all TWs:

$$\max \sum_{f \in F, t \in T_f^0} x_f(t) \cdot \gamma(t - d_f) \tag{12}$$

Cost coefficients γ ensure that TW durations are distributed as fairly as possible, i.e. the model will favour the assignment of TWs of similar duration to each of two flights, rather than the assignment of a large TW to one flight and a small one to another.

$$\gamma(\tau) = 1 - \frac{\tau}{w_{max} \cdot |F|}, \qquad 0 \le \tau \le w_{max} - 1 \tag{13}$$

2.2.4 Constraints

2.2.4.1 Definition constraints for decision variables

Decision variables $x_f(t)$ are binary, monotone decreasing variables.

$$x_f(t) \ge x_f(t+1), \qquad \forall f \in F, t \in T_f^0 \tag{14}$$

$$x_f(t) \in \{0, 1\}, \qquad \forall f \in F, t \in T_f^0 \tag{15}$$

2.2.4.2 Time Window duration constraints

There are two TW duration constraints – minimum and maximum duration constraints. The minimum duration constraint guarantees that the specified minimum duration for TWs is respected, by taking advantage of the fact that decision variables are monotone decreasing as imposed by constraint 14.

$$x_f\left(d_f + w_{min} - 1\right) = 1, \qquad \forall f \in F \tag{16}$$

The maximum duration constraint defines the set T_f^i containing a number of time periods that is equal to the maximum TW duration w_{max}.

$$T_f^i \equiv \left\{ d_f + l_{r_f}^i, \ldots, d_f + l_{r_f}^i + w_{max} - 1 \right\}$$

2.2.4.3 Capacity constraints

Capacity constraints ensure that sector and airport capacities are respected for all sector-hours. As was already mentioned, the capacity is defined as the number of entries into the sector during an hour. If the trajectories assigned by the SATA model are flown with the accuracy of one minute, then all the sector-hour capacities defined in the network are respected. However, the point of the TW model is to determine how much flexibility in terms of time can be assigned to each trajectory. To be able to optimally assign the TWs, we need to take into account the possibility that the TW can extend into the following sector-hour, as depicted in Figure 3. The depicted trajectory is planned to enter the blue sector at 8:55 (sector-hour 8 – SH8), respecting the capacity. If there are no other flights scheduled to enter the sector and/or there is spare nominal capacity, we can assign 5 minutes of flexibility to this flight.

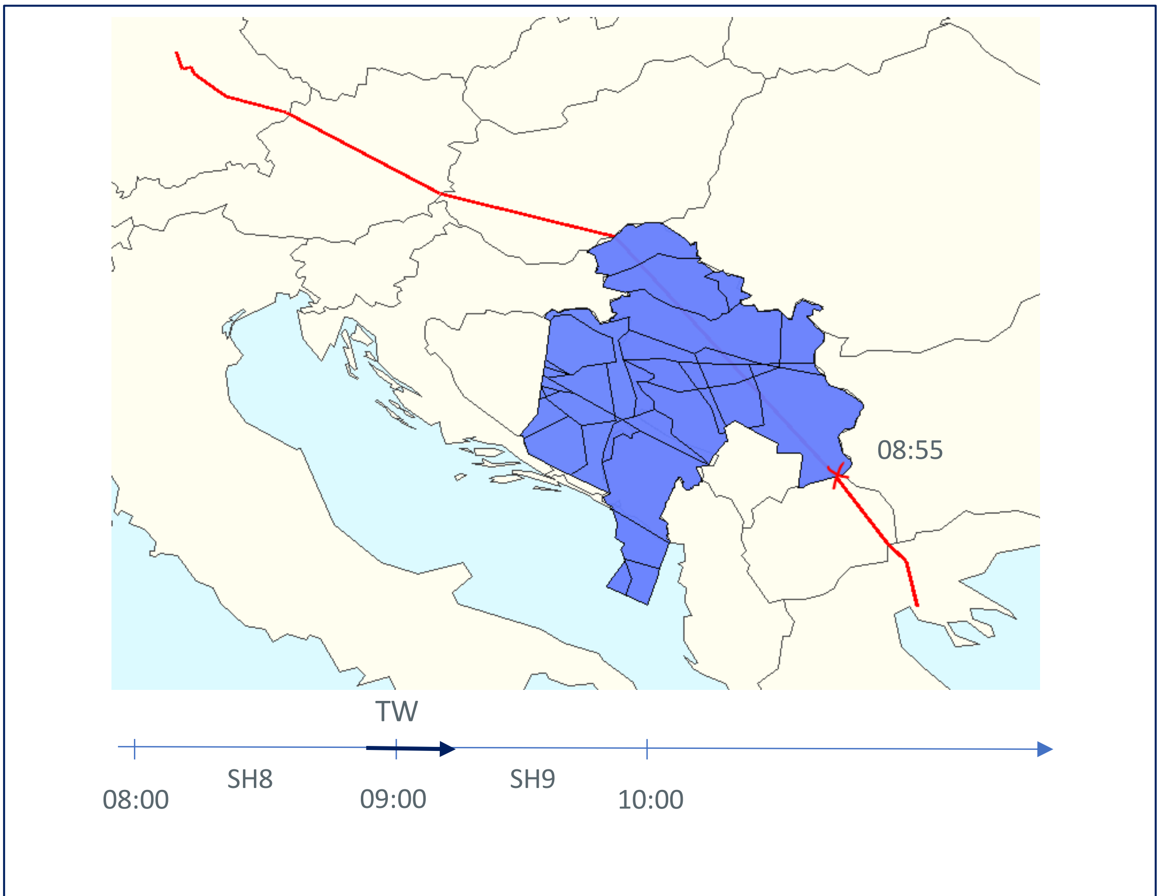

Figure 3. TW extending across two sector-hours.

In order to extend the TW for more than 5 minutes, we will need to reserve one unit of capacity in the following sector-hour (SH9) for the duration of TW.

With that in mind, to simplify the definition of capacity constraints, we use additional logic parameters:

- $v^i_{f,t}(c)$ determines whether time period t is the first period of TW, or the first period of opening of the sector-hour c :

$$v^i_{f,t}(c) \coloneqq \left(t = d_f + l^i_{r_f}\right) \bigvee (t = open_c)$$

- $in^i_f(c)$ determines whether the TW for flight f, that may reserve capacity in sector-hour c, in the i –th element of its route, starts before the opening of sector-hour c:

$$in^i_f(c) \coloneqq d_f + l^i_{rf} < open_c < d_f + l^i_{rf} + w_{max} - 1$$

- $out^i_f(c)$ determines whether the TW for flight f, that may reserve capacity in sector-hour c, in the i-th element of its route ends after the closure of sector-hour c:

$$out^i_f(c) \coloneqq d_f + l^i_{rf} < close_c < d_f + l^i_{rf} + w_{max} - 1$$

Thus, the capacity constraints can be expressed as:

$$\sum_{\substack{f\in F, t\in T^c: \\ orig_f = a \wedge v^0_{f,t}(c)}} x_f(t) \le Q_c, \qquad \forall a \in A,\ c \in C^{dep}_a \tag{17}$$

$$\sum_{\substack{f\in F, t\in T^c: \\ dest_f = a \wedge v^{n_f-1}_{f,t}(c)}} x_f(t - l^{n_f-1}_{r_f}) \le Q_c, \qquad \forall a \in A, c \in C^{arr}_a \tag{18}$$

$$\sum_{\substack{f\in F, t\in T^c: \\ orig_f = a \wedge v^0_{f,t}(c)}} x_f(t) + \sum_{\substack{f\in F, t\in T^c: \\ dest_f = a \wedge v^{n_f-1}_{f,t}(c)}} x_f(t - l^{n_f-1}_{r_f}) \le Q_c, \forall a \in A, c \in C^{gen}_a \tag{19}$$

$$\sum_{\substack{f\in F, i\in[1, n_f-2]: \\ s^i_{r_f} = s \wedge v^i_{f,t}(c)}} x_f(t - l^{n_f-1}_{r_f}) \le Q_c, \qquad \forall s \in S, c \in C^{ent}_s \tag{20}$$

The constraint (17) imposes the departure capacity at the airport (if defined), the constraint (18) the arrival and constraint (19) the general airport capacity. The constraint (20) imposes sector capacity.

2.3 Variants of TW model

2.3.1 Conservative TW model

Previous section (section 2.2) presents the initial version of the TW model, that we term the ***conservative model***. The model described above could lead to overly conservative solutions since it may reserve an excessive amount of capacity for each flight: in case a TW extends over two sector-hours (see Figure 3), the model reserves a whole unit of capacity, even though the flight will use only one unit of capacity in either of the two sector-hours.

(Castelli, et al., 2011) presented two alternative approaches to computing the utilisation of the capacity in order to avoid too conservative solutions. Adopting the reasoning by Castelli et al, we develop two further variants of the TW model:

- Proportional model;
- Intermediate model.

These two model variants are obtained by varying the capacity constraints 17, 18, 19 and 20 presented above.

2.3.2 Proportional TW model

Proportional model. In this variant, a fraction of unit of capacity is assigned to each period of TW duration, where the fraction is obtained by dividing the unit of capacity by the number of periods in the TW (duration). As an example, if there is a 5-period TW, two of which are within the sector-hour $c1$, and the remaining three are within the sector-hour $c2$, only ${}^{2}/_{5}$ of the unit of capacity will be reserved in sector-hour $c1$, and the ${}^{3}/_{5}$ will be reserved in $c2$.

To put this in practice, as the TW duration is determined in the optimisation model, we introduce the following:

- β as the capacity utilisation coefficient for each period of the TW duration, $\beta \epsilon [0, 1]$;
- δ as the number of periods of the TW falling within the first sector-hour;
- τ as (any) remaining periods of TW falling within the second sector-hour. $\tau \in [\delta;\ w_{max} - 1]$

Thus, the new capacity utilisation coefficients $\beta(\delta, \tau), \tau \geq \delta$ are defined as follows:

$$\beta(\delta,\tau) = \begin{cases} \dfrac{1}{\tau+1}, & \text{if } \tau = \delta; \\ \dfrac{\delta}{\tau(\tau+1)}, & \text{if } \tau > \delta \end{cases} \qquad \forall \delta, \tau \in [0; w_{max} - 1], \tau \geq \delta \tag{21}$$

Table 1 shows an example of the capacity utilisation coefficients $\beta(\delta, \tau)$ for the TW of the duration 5 ($w_{max} = 5$).

Table 1. Example of capacity utilisation coefficients

	$\tau = 0$	$\tau = 1$	$\tau = 2$	$\tau = 3$	$\tau = 4$
$\delta = 0$	1	0	0	0	0
$\delta = 1$		$\frac{1}{2}$	$\frac{1}{6}$	$\frac{1}{12}$	$\frac{1}{20}$
$\delta = 2$			$\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{10}$
$\delta = 3$				$\frac{1}{4}$	$\frac{3}{20}$
$\delta = 4$					$\frac{1}{5}$

Thus, in the proportional model, the constraint 17 becomes:

$$\sum_{\substack{f \in F, i \in [1, n_f - 2], t \in T^c \cap T_f^i: \\ s_{r_f}^i = s \wedge in_f^i(c)}} \beta\left(open_c - (d_f + l_{r_f}^i), t - (d_f + l_{r_f}^i)\right) \cdot x_f(t - l_{r_f}^i) \tag{22}$$

$$+ \sum_{\substack{f \in F, i \in [1, n_f - 2], t \in T^c: \\ s_{r_f}^i = s \wedge v_{f,t}^i(c) \wedge \neg in_f^i(c)}} x_f\left(t - l_{r_f}^i\right)$$

$$- \sum_{\substack{f \in F, i \in [1, n_f - 2], t \in T_f^i \setminus T^c: \\ s_{r_f}^i = s \wedge out_f^i(c)}} \beta\left(open_c - (d_f + l_{r_f}^i), t - (d_f + l_{r_f}^i)\right) \cdot x_f\left(t - l_{r_f}^i\right) \leq Q_c,$$

$$\forall s \in S, c \in C_s^{ent}$$

2.3.3 Intermediate TW model

In this variation of the TW model, we reserve the whole unit of capacity for the portion of the TW duration that falls within the first sector-hour, and a fraction of the unit of capacity for all the remaining periods of the TW that fall within the second sector-hour. Taking up the previous example, if there is a 5-period TW, two of which are within the sector-hour $c1$, and the remaining three are within the sector-hour $c2$, one unit of capacity will be reserved in sector-hour $c1$, and the $^{3}/_{5}$ of the capacity unit will be reserved in $c2$.

Thus, the capacity constraint 20 from the conservative TW model becomes:

$$\sum_{\substack{f\in F, i\in[1,n_f-2], t\in T^c \cap T_f^i: \\ s_{r_f}^i = s \wedge in_f^i(c)}} \beta\left(open_c - (d_f + l_{r_f}^i), t - (d_f + l_{r_f}^i)\right) \cdot x_f(t - l_{r_f}^i) \tag{23}$$

$$+\sum_{\substack{f\in F, i\in[1,n_f-2], t\in T^c: \\ s_{r_f}^i = s \wedge v_{f,t}^i(c) \wedge \neg in_f^i(c)}} x_f\left(t - l_{r_f}^i\right), \forall s \in S, c \in C_S^{ent}$$

Note that the constraint 23 does not contain the last negative component of the constraint 22 of the proportional model.

$$-\sum_{\substack{f\in F, i\in[1,n_f-2], t\in T_f^i \setminus T^c: \\ s_{r_f}^i = s \wedge out_f^i(c)}} \beta\left(open_c - (d_f + l_{r_f}^i), t - (d_f + l_{r_f}^i)\right) \cdot x_f\left(t - l_{r_f}^i\right) \leq Q_c,$$

This component has the task of discounting the amount of capacity of an sector-hour c reserved for those flights that enter the sector in the a subsequent sector-hour because the relative time window ends after the closure of sector-hour c (and opening of the sector-hour $c1$).

3 Data instance

The EFPS model is run on a day of real air traffic data, encompassing the entire European Civil Aviation Conference (ECAC) airspace. Different data items are needed to run the models formulated in the section 2, 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 & Tanner, 2015).

The deliverable description states that the deliverable will contain the formulation and the small-medium to large scale examples. As we preferred to test the model on the large-scale examples, we use the data instance created with the traffic from September 12th, 2014, and the new data instance based on the September 1st 2017 is being prepared and run for the more extensive computations and mitigation actions that will be presented in the deliverable D3.2.

3.1 Flights

The flight data is taken from September 12th 2014, that counted 33 810 flights. However, we exclude the military flights, overflights, helicopters, and flights departing from and arriving at the same airport, thus ending with the 29 270 flights.

3.2 Airspace configuration and capacities of resources

Each Area Control Center (ACC) usually changes the configuration of the active sectors several times throughout the day, to best accommodate the changing traffic demand (both number of flights and flow directions). The EFPS model applies changing sector configurations, the ones in place in Europe on September 12th 2014, which counted 204 airports and 1182 sectors (this is the total number of different sectors that were open at some point on the chosen day, they are not all open/active at the same time). The capacity of active sectors is also needed, in order to define the capacity constraints (17-20, 22,23). We sourced the airport and sector nominal capacities from the DDR2 data.

3.3 Aircraft types and related flight costs

Cook and Tanner (2015) report contains detailed assessment of strategic and tactical operational costs for crew, fuel, aircraft and fleet maintenance. The costs are detailed for 15 most commonly used aircraft types in Europe, and are divided in the following three cost profiles: low, base and high. To be able to estimate operational costs for the flights in the model, all the different aircraft types appearing in the data set are grouped into 15 clusters. The clustering uses the square root of the maximum take-off weight (MTOW) of the 15 mentioned reference aircraft types as the clustering criterion. MTOW values are taken from DDR2 *.mwc data file. The file contains the MTOW in metric tonnes for each aircraft type appearing in the AIRAC cycle.

3.4 Airline types and cost profiles

Airlines operating the flights included in the input data are divided into four types: full-service, low-cost, charter, and regional. The airline type classification allows us to assign each of the flights to one of the three flight cost profiles:

- 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.

Hub airports are those of the ACI EUROPE's "Group 1", comprising of 14 ECAC airports with over 25 000 000 passengers in 2014. The cost profiles are used to define operational flight costs used in the SATA model. Thus, the categorisation of flights results in:

- 17% of low cost flights;
- 28% of high cost flights, and
- 55% of base cost flights.

3.5 Routes and departure times

For each Origin-Destination (OD) – aircraft type combination we determine a set of routes to be used by the EFPS model. The routes are sourced from the first two weeks of the 1409 AIRAC. However, to reduce a number of routes, we consider only the ones that differ significantly from one another in terms of geographical distance (more than 20 kilometres where the distance between the two routes is maximal). The departure times are in the range of 30 minutes before and after the requested time, which is taken from the m1 files of DDR2 data.

3.6 Route charges and unit rates

Unit rates for September 2014 for all States signatories of the Multilateral Agreement relating to Route Charges (EUROCONTROL, CRCO, 2015) are taken from DDR2 Central Route Charging Office (CRCO) route charges files (which are the same as the ones that can be found on the CRCO's website). Estonia and Ukraine are also included as their integration in route charging system was underway in 2014, their unit rate values are sourced from the respective ANSP websites.

4 Computational experiments

Previous sections introduced the aim of the ADAPT solution, mathematical formulation of the EFPS model (SATA and TW mixed-integer programming models), and the data instance used for the computational experiments. In this section, we describe different computational experiments and their results. As the SATA model has been already developed and tested in the SATURN project and the detailed analysis of results has been published in Bolic et al. (2017), here we focus on the results of the TW model. However, it is important to keep in mind that the SATA model is the input of the TW model, thus the TW model results reflect the results of the SATA model as well.

4.1 Results

The ADAPT solution is founded on the EFPS model, which in turn is composed of SATA and the TW model. To reiterate, the SATA model is run first and it assigns the trajectories and departure times to all flights. Then the TW model is run to determine the flexibility (TW) of each flight. As was described, we have three variants of the TW model: conservative, proportional and intermediate. We show and discuss the results for the three model variants.

Before we discuss the results, we need to introduce a few definitions:

- Constrained flight - is a flight f that is assigned a TW, the duration of which is w^f time-periods shorter than the maximum TW w_{max}.
- Saturated sector-hour - a sector-hour where some (constrained) flights cannot reserve capacity for later execution of their corresponding operation[5] because the capacity limit has been reached.
- Criticality index k_c - measures the degree of criticality of a sector-hour as the total *additional* number of the time periods that all flights constrained by the same sector-hour would have if it had sufficient capacity. On the whole, the criticality index of a sector-hour is overestimated as the constrained flight could be limited by multiple sector-hours. The criticality index k_c is:

$$k_c = \sum_{f \in F_k^c} (w_{max} - w^f)$$

[5] Operation can be entry into sector, or arrival, departure or mix of arrival/departures to/from an airport.

Where F_k^c is the set of constrained flights that have time window duration constrained by the limited capacity of the saturated sector-hour c.

Computational experiments were run on a 64 bit Intel(R) Xeon(R) E5520 @ 2.27GHz quad core CPU computer, having 16GB of RAM memory and Debian 8.0 operating system. For the SATA model, the optimality gap is set to 1%, and the computation time is between 250 and 310 seconds, depending on the choice of the objective function (minimum shift, or minimum cost, see section 2.1.3).

The computational times for the TW model variants are reported in Table 2. The run times increase with the maximum duration of the TW. For the conservative TW model, the optimal solutions are found, while for the intermediate and proportional model the optimality gap is set to 1%. The conservative TW model is the fastest, with the proportional model being the slowest.

Table 2. Run times of TW model variants for three different maximum TW durations.

TW_{max} (min.)	Conservative	Intermediate	Proportional
10	2,69 s	3,61 s	3,93 s
15	3,41 s	7,83 s	514,00 s
20	5,53 s	14,49 s	8825,00 s

4.1.1 TW duration

As the minimum and maximum duration of the TW are the parameters, here we explore, for all three TW models:

- Minimum TW duration of 1, 2 or 3 minutes;
- Maximum TW duration of 10, 15 and 20 minutes.

Figure 4 shows the proportion of constrained (termed critical[6] on the graph) and flexible (non-critical) flights in function of the chosen maximum duration of the TW, across the three TW model variants. In all the cases, the conservative TW model flags the highest number of critical flights, which is to be expected as it reserves the most capacity when calculating the TW duration. Further, the intermediate model always identifies less critical flights than the conservative model, but more than the proportional model.

What can also be noted is that as we increase the maximum duration of the TW, the number of constrained flights increases, which is to be expected according to the above definition of critical (constrained flight).

[6] The terms constrained and critical flights are used interchangeably in the presented graphs.

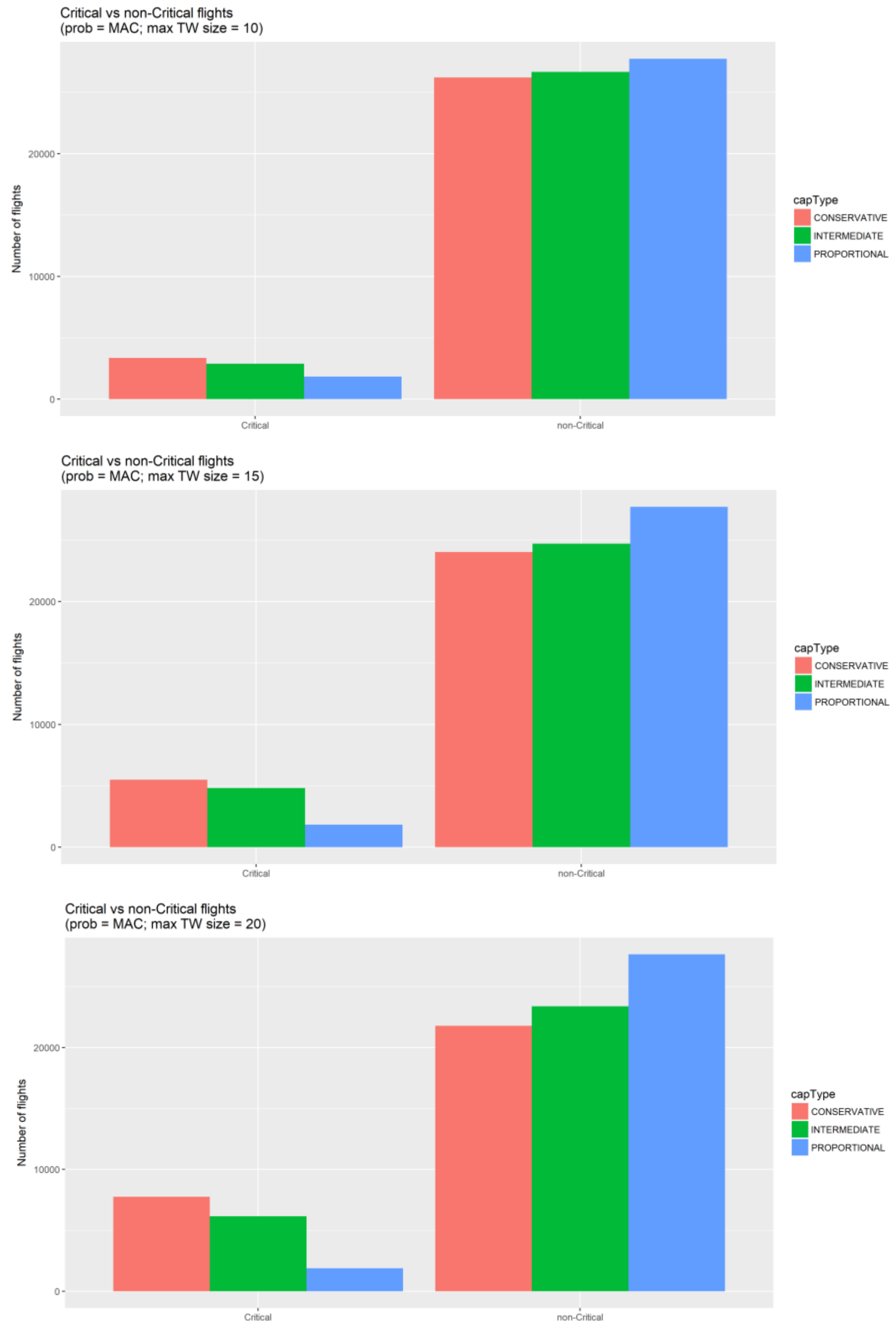

Figure 4. Proportion of constrained (critical) and flexible (non-critical) flights, depending on the maximum TW duration (top TW=10 min, center TW=15min, bottom TW=20 min).

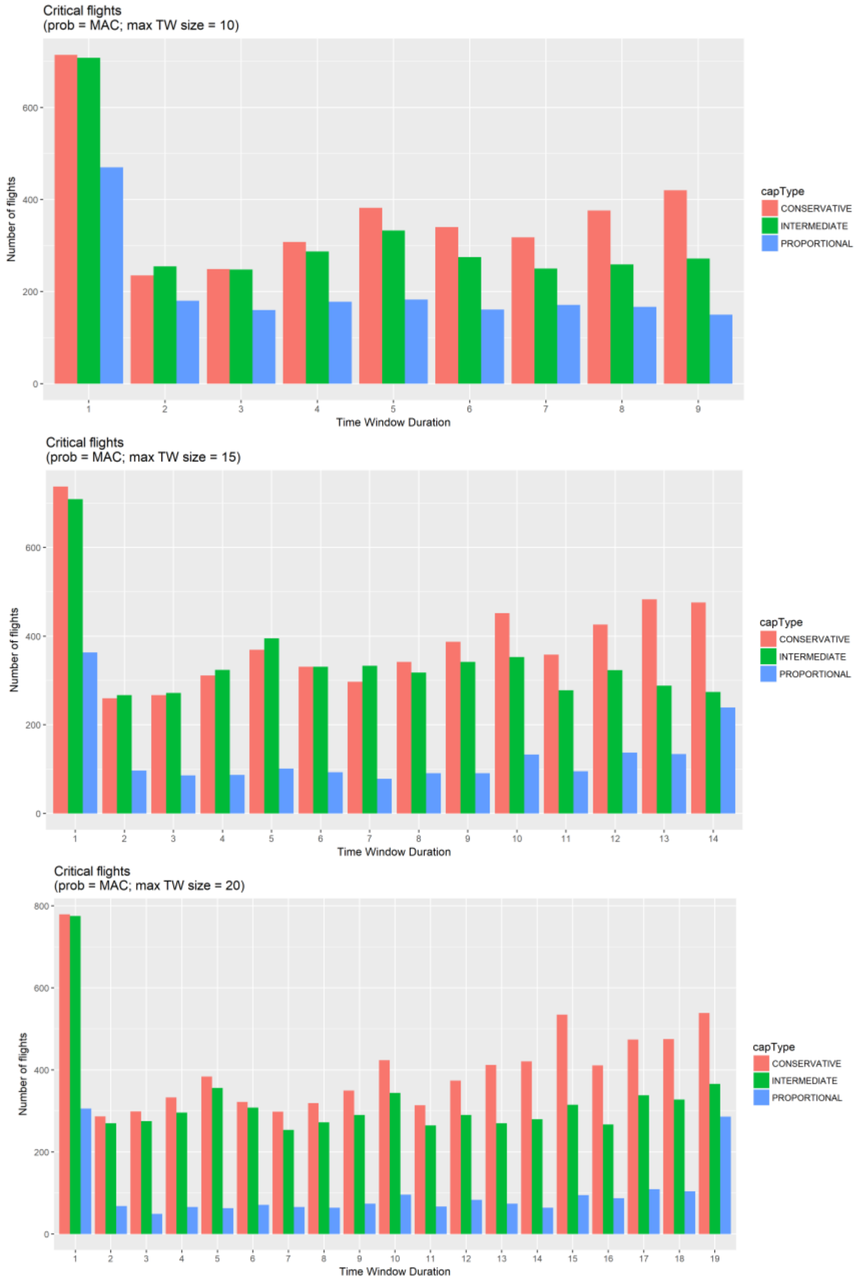

Figure 5. Number of constrained flights, divided by the assigned TW duration, across three model variants (top, TW=10 min., center TW=15 min., bottom TW=20min.).

Figure 5 depicts the number of constrained flights with the TW duration that is lower than the maximum allowed, across three TW model variants, for the three maximum durations (10, 15 and 20 minutes). Figure 4 showed that the lowest number of constrained flights is obtained by using the proportional model (blue bars), which continues to be the case for all the TW durations lower than the allowed maximum. The intermediate model continues to perform better (lower number of constrained flights for each duration) than the conservative model.

Further, our results show that increasing the minimum duration of the TW has no impact on the total number of constrained flights. Figure 6 shows the proportion of constrained and non-constrained flights for the conservative model and TW duration of 20 minutes, when the minimum TW duration is changed (1,2, or 3 minutes). We do not show the results for intermediate and proportional models as they show the same trend.

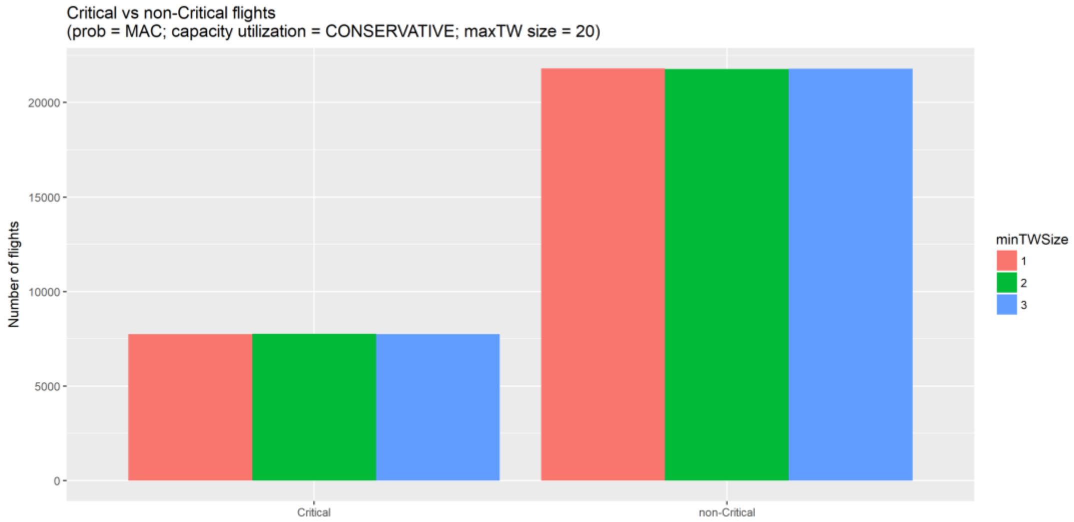

Figure 6. Proportion of constrained (critical) and non-constrained flights in the conservative TW model, for different minimum TW durations assigned (1,2, or 3 minutes).

To sum up, there are clear differences between the three TW models, proportional model being the one that identifies the lowest number of constrained flights. It is important to note that even in the worst case (conservative TW model, TW of 20 minutes), about 25% of total daily flights are identified as constrained, out of which only a small portion (less than 3% of total daily flights) are heavily constrained (TW of 1 minute). Most of other flights identified as constrained still have some flexibility, and what is more, this flexibility is quantified – each flight is assigned a TW of a certain duration.

4.1.2 Constrained flights and saturated sector-hours[7]

The EFPS model (composed of SATA and TW model) assigns the trajectory, departure time and the flexibility (duration of TW) for all the flights. Apart from that, we can identify which are the network elements that impose limits on the flight's flexibility. Two flights constrained by four sector-hours are depicted in the Figure 7. A flight from Malaga (LEMG) to Stockholm Arlanda (ESSA), with the TW of 8 minutes is shown in the left figure. In the right part of the figure a very constrained flight, from Almeria (LEAM) to Helsinki with the TW of 1 minutes is shown.

The interesting result is that most of the flights are not constrained. The Figure 8 shows the proportion of non-constrained flights, and further divides the constrained flights into the ones constrained by one,

[7] Examples shown in this section are the results of the intermediate TW model with the TW of maximum duration of 15 minutes.

two, three or four sector-hours. Majority of the constrained flights (3828 out of 4807) are limited by only one sector-hour.

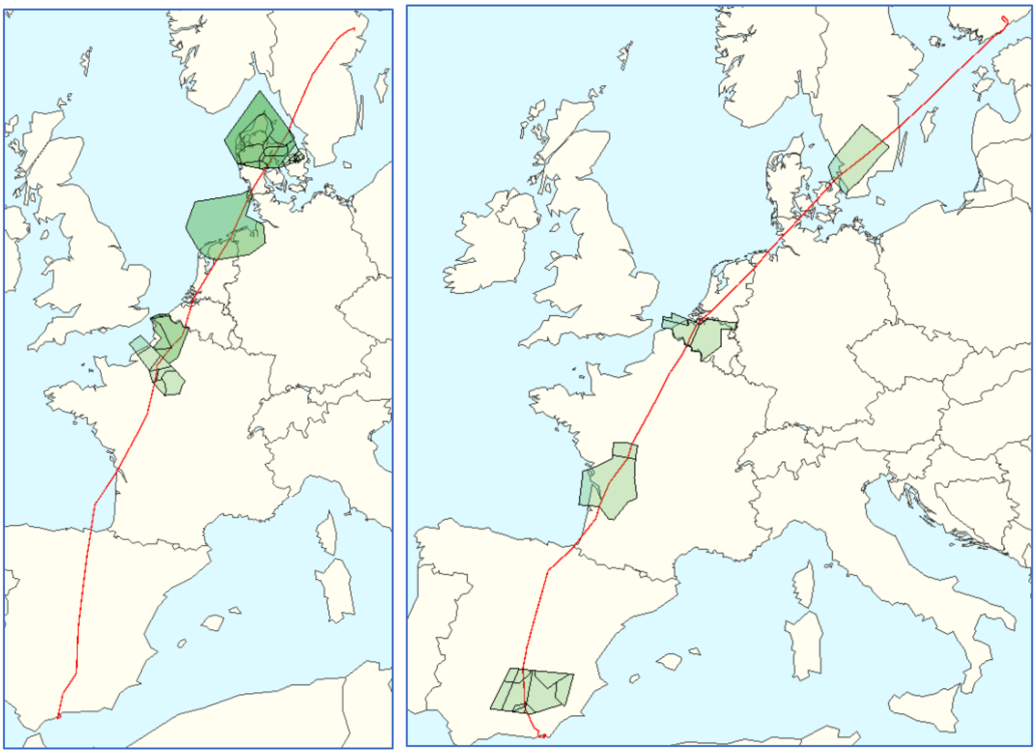

Figure 7. Example of two flights constrained by four sector-hours: flight from LEMG to ESSA on the left, flight from LEAM to EFHK on the right.

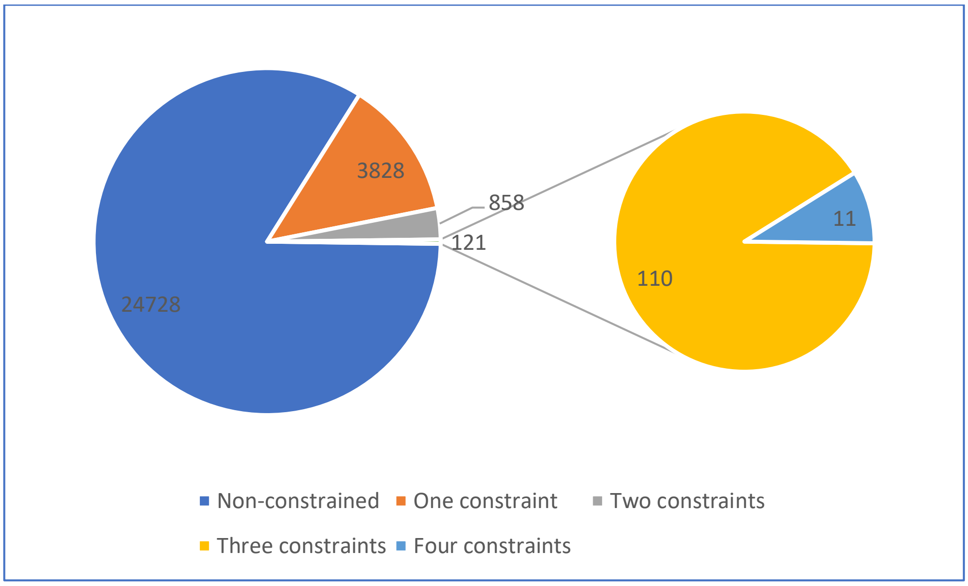

Figure 8. Proportion of non-constrained versus constrained flights.

Furthermore, from the results, we can identify the saturated (hotspots) sector-hours in the network. An example of geographical location of saturated sectors in the hour between 09:00 and 10:00 is shown in Figure 9.

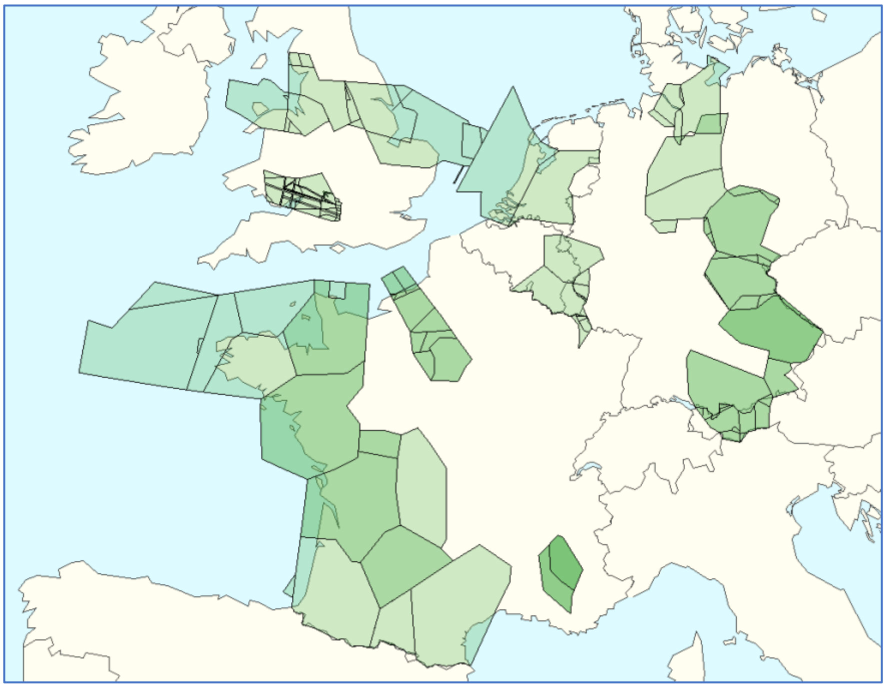

Figure 9. Sample of saturated sector-hours between 09:00 and 10:00.

4.2 Feasibility

As explained in more detail in the section 1.1, a time window is a time interval describing the flexibility (in time dimension) of a trajectory. A time window indicates how “late” (with respect to declared timing of the trajectory) a flight can be and still not create capacity-demand imbalances in the network. In section 0 we described the three variants of the TW model. The TWs assigned by the conservative model respect the capacity. On the other hand, this limits the flexibility (i.e. duration of TWs) that can be given to flights. The proportional and intermediate models attempt to extend this flexibility, by reserving only a fraction of capacity, which when applied on the whole network may result in the breach of some of the capacity constraints. As this would be counterproductive, this first experiment tests the feasibility of the proportional and intermediate models with respect to the eventual breach of capacity constraints.

In order to test the feasibility, we simulate the utilisation of capacities of all sector-hours for both intermediate and proportional models, using the approach proposed by (Castelli, et al., 2011). The simulation is performed by assigning random departure delay within the assigned TW. This delay then shifts the times of entry into the sectors (and landing at the destination airport) along the trajectory, and we collect the capacity utilisation numbers for all sector-hours. In the final step of the simulation the capacity utilisation of sector-hours is compared with the sector-hours' nominal capacities, to determine if the capacity constraints were violated or not.

The simulation of departure delay is performed using the following three probability distribution functions:

- Uniform: all time periods within a time window can be chosen with equal probability.
- Triangular-like: the probability monotonically decreases with time and hence the first time period has the highest probability and the last time period the lowest.
- Mixed: the initial time period has 0,5 probability to be chosen, whereas all the other time periods equally share the remaining probability.

We run 100 000 simulations for each combination of the TW model (intermediate and proportional), probability distribution (uniform, triangular-like, mixed), and the maximum duration of TW (10, 15 or 20 minutes). Each simulation was run for about 29 000 flights, over about 20 000 sector-hours[8].

Table 3. Percentage of sector-hours for which the capacity is violated. (Values averaged over 100 000 random instances)

	Intermediate			Proportional		
TW duration	**Uniform**	**Triangular-like**	**Mixed**	**Uniform**	**Triangular-like**	**Mixed**
10	0,062	0,015	0,024	0,492	0,454	0,478
15	0,107	0,018	0,035	0,735	0,793	0,690
20	0,106	0,020	0,020	0,829	0,917	0,783

Table 3 shows the percentage of sector-hours for which the capacity is violated. These values are the average values across 100 000 simulations. Just for illustration, in case of the intermediate TW model, TW duration of 15 minutes, tested with the uniform distribution, this results in about 21 sector-hours (0,107% out of 20 000 sector-hours) having their capacity violated. The tests in which the uniform delay distribution is applied have higher numbers of capacity violations than the tests with the triangular-like and mixed delay distribution.

Apart from knowing that the capacity is respected or not, it is important to know the number of excess flights:

- For intermediate TW model: on average (across 100 000 runs) from 1,06 to 1,28 flights;
- For proportional TW model: on average from 1,32 to 1,69 flights.

For further illustration, the maximum number of flights exceeding sector-hour capacity in these simulations is 13, and there are just a few such instances across all the simulations (100 000 simulations per each combination described above). For example, the sector depicted in Figure 10 had in a few

[8] Note that term sector-hours includes airport hourly capacities (that can be general, arrival and/or departure).

cases 11 or 13 flights exceeding its capacity within several sector-hours (sector-hour capacity is 76). The inspection of the actual entry count data for this particular sector reveals that the entry count is often higher than its nominal capacity, going up to 100 flights an hour. Thus, such high numbers of flights exceeding the capacity happened only a few times in our simulations, and even those excesses fall within the regular operations.

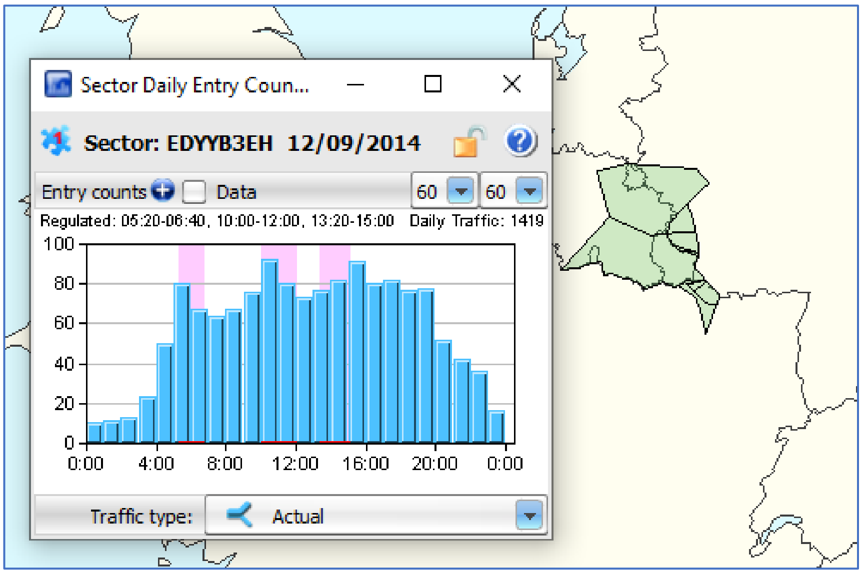

Figure 10. Sector that had a few significant capacity violations in the simulations for feasibility testing.

From the results presented in the Table 3, the intermediate TW model presents significantly lower number of capacity violations than the proportional TW model. As intermediate TW model reserves the capacity in a less constraining manner than the conservative model, and results in less capacity violations in the feasibility simulations than the proportional TW model, it is the preferred TW model variant that we will be bringing forward.

4.3 Sensitivity

As the TW models are integer programming problems, it is not possible to perform a sensitivity analysis as in the case of linear programming problems. Here, we propose an alternative approach to a sensitivity analysis, using the criticality index introduced in section 4.1. In our approach, we calculate the criticality index for all the sector-hours in the modelled instance. The high criticality index denotes the sector-hours for which an increase of capacity would bring the greatest benefit to the increase of the value of the objective function.

In Table 4 we show the fifteen sector-hours with highest criticality index from the intermediate TW model, with the TW_{max}=15 minutes, out of 581 saturated sector-hours identified by this model. For each sector-hour the start time, end time, capacity, number of constrained flights, and the criticality index is shown. As can be seen only the first four sector-hours constrain a relatively high number of flights, when compared to their respective capacity.

Table 4. Criticality index for a sample of sector-hours (intermediate TW model, TW_{max}=15 min.)

Location	Start Time	End Time	Capacity	Constrained flights	Criticality index
EGTTSOUTH	21:00	22:00	31	40	462
EGTTEAST	20:00	21:00	38	32	329
LPPCNXUPP	18:00	19:00	43	20	169
EDUUSAL1A	11:00	12:00	51	20	162
EDYYD4WH	18:00	19:00	62	17	161
EDYYDHOL	14:00	15:00	59	18	160
LFBBL4	06:00	06:30	18	16	158
EDYYB3WH	06:00	07:00	66	19	157
LGGGRDS	08:00	09:00	39	14	157
LFBBP123	19:00	20:00	47	14	156
EGTTDTS	05:30	06:00	28	12	153
EDUUDON1D	10:00	11:00	54	21	151
EDUUERL1R	10:00	11:00	54	14	148
EGTTDTS	06:00	07:00	56	17	148
EDYYB3EH	10:00	11:00	76	17	144

The sensitivity analysis we propose consists of identifying all the saturated sector-hours and calculating their criticality index in order to identify the most constraining sector-hours. Then, for the 5% of the saturated sector-hours with top values of criticality index, we increase the capacity for 5% (rounding to the integer value), and run the EFPS model (SATA and TW model) with the new capacity values.

Figure 11 and Figure 12 show the results of the increase of the capacity for the 5% of the most critically saturated sector-hours (intermediate[9] TW model, TW_{max}=15 min.). It can be seen that the number of constrained flights decreases, after the capacity increase of a number of sector-hours, showing that

[9] For the simplicity we present just the results of the intermediate model. Both conservative and proportional TW model results of the sensitivity analysis behave in the same manner.

the TW model behaves as predicted. Furthermore, the number of constrained flights decreases for every TW duration lower than 13 minutes, and increases afterwards.

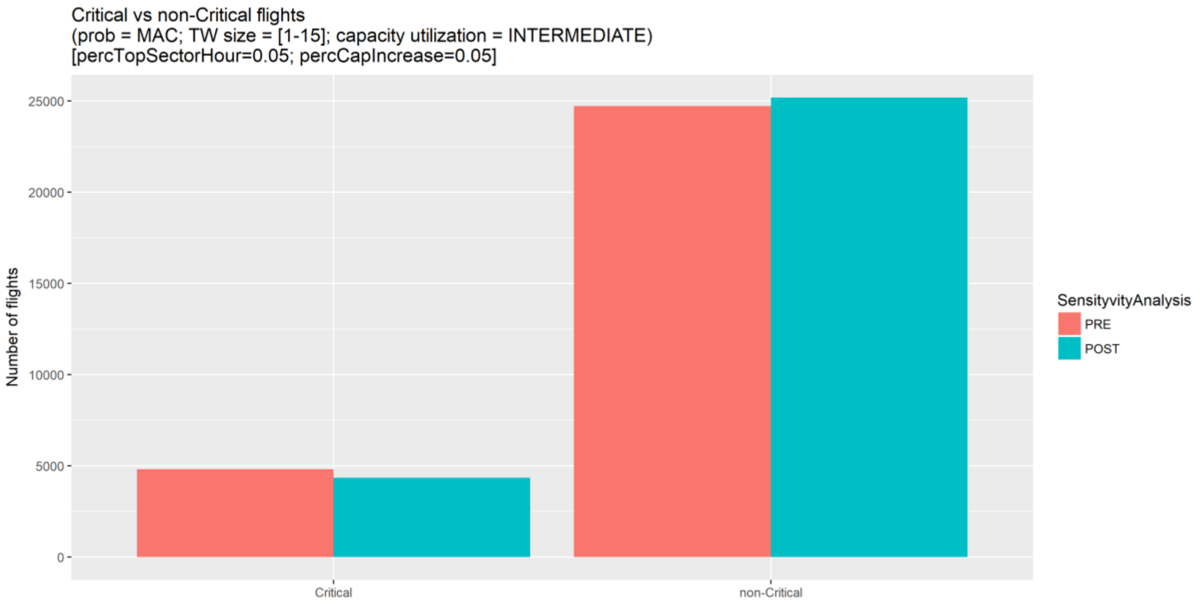

Figure 11. Proportion of constrained (critical) and non-constrained flights before (pre) and after (post) capacity increase for the 5% of saturated sectors, for the intermediate TW model, with TW_{max}=15min.

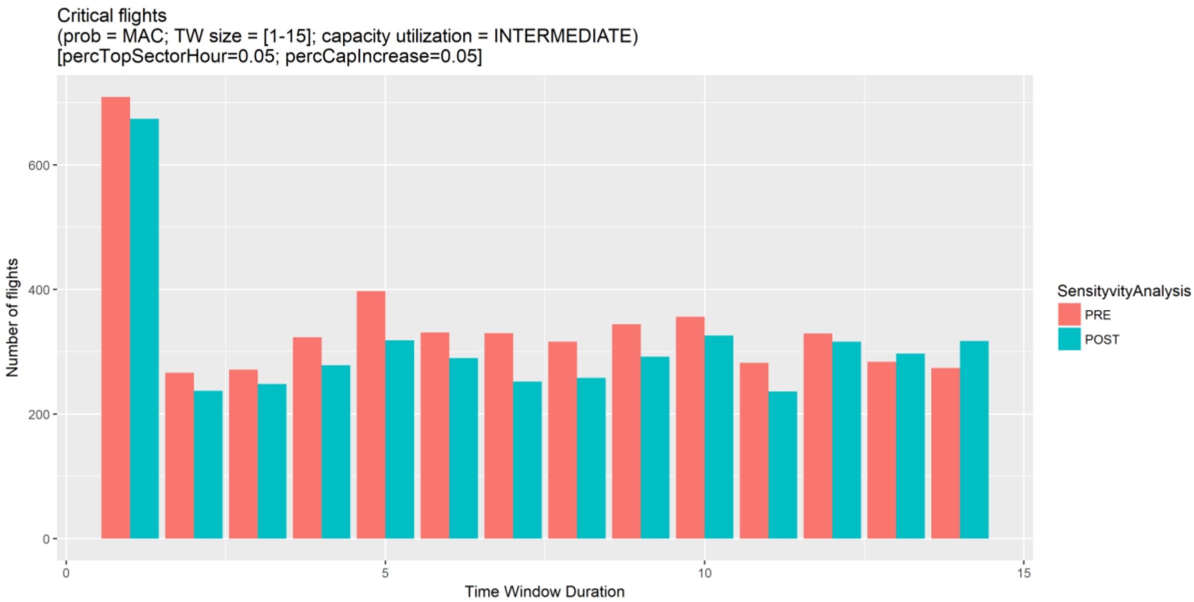

Figure 12. Number constrained flights across the assigned TW duration, before and after the capacity increase.

5 Conclusions and next steps

5.1 Discussion

Here we presented the mathematical formulation of EFPS model, which is composed of SATA and TW integer programming models. The SATA model has been developed and tested in SATURN project, and the results published. However, as it is a part of the EFPS model, we repeated the mathematical formulation as presented in (Bolic, et al., 2017). Furthermore, the TW model formulation, and its three variations are presented. The computational experiments are the result of the application of the EFPS model (as SATA results are input for the TW models), even though we focus on the end-results coming out of the TW models.

It is important to reiterate that the intended use of the EFPS model is in the strategic phase (e.g. before flight schedules are published), and that departure and arrival times earlier or later than the requested ones may be assigned by the SATA model. 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. Thus, we assume that shifts assigned so much in advance would not impact the tail-number dependencies. However, both SATA and TW model formulation include the tail-number dependency constraints (i.e. turnaround constraints, see Appendix A). As we do not have access to the tail number data for the real-life data instance used, the turnaround constraints were not applied in the work presented here. The lack of turnaround constraints limits the possible uses of the EFPS model to the strategic phase only. For the tactical use, the turnaround constraints are instrumental, as well as the impact it would have on the run time of the model.

Regarding the flexibility measure (TW), based on the results presented in the section 4, the intermediate TW model is the preferred TW model: it reserves the capacity in a less constraining manner than the conservative model, and results in less capacity violations than the proportional TW model. We tested different TW durations – 10, 15 or 20 minutes. It is our opinion that the TW of 15 minutes is most useful, as it requires less of unnecessary capacity reservations, and is of the same length as the ATFM slots. However, as both the minimum and maximum durations of TWs are the parameters of the model, they can always be changed.

The EFPS model assigns the trajectory, departure time and flexibility measure (TW) for all the flights in the data instance (the ECAC network for the entire day of traffic). Apart from that, for each constrained flight the limiting sector-hour is identified, which can be of help in case the airline user would prefer to re-rote the flight in order to increase its flexibility.

Furthermore, the TW model gives the list of saturated sector-hours throughout the day. Keep in mind that the configurations are changed during the day. Having the information on the saturated sectors, and their criticality index, the ANSPs could take mitigation actions in order to improve the situation. For example, a supervisor having one or two saturated sectors, both with the low criticality index, might decide that the current configuration is good enough as even if the capacity ends up being violated it will be for a small number of flights, which in many cases is what already happens in every-day operations. However, if there are few sector-hours within an ACC that have high criticality indexes, the supervisor might decide to change the configuration into a one that brings more capacity.

As EFPS model is aimed at the strategic/pre-tactical flight planning phase, it can be used in the further analysis of the system performance by different stakeholders – airlines, ANSPs, airports and Network Manager. As the models are fast, they could also be used in the what-if scenarios, for example re-routing or change of configuration.

Note that the models are not intended for the tactical use. In order to be suitable for tactical use, several things would need to be added: the turnaround constraints, the higher-resolution capacity constraints, possibility of dynamic re-routing, just to mention the main components. However, these would increase the complexity, the computational times, and might end-up infeasible for large data instances.

5.2 Next steps

This deliverable contains the mathematical formulation of EFPS model and the results of the initial large-scale computational experiments. In order to fully assess the model, the next steps within WP3 will consist of:

- Application of EFPS model on the newer data instance, that is to say for September 1st 2017.
- Mathematical verification of ADAPT solution (application of EFPS model) by the way of comparing baseline (no ADAPT) and solution scenarios, as defined in (ADAPT, 2018).
- Application and assessment of strategic mitigation scenarios as presented in the Deliverable D2.1. (ADAPT, 2018)
- Development of quantitative evaluation of the (economic) risk associated with each sector and definition of its severity.

In order to capture all the different angles of these assessments, ADAPT will make use of relevant assessment metrics, the initial set of which was defined in ADAPT, 2018.

The EFPS model results on this data instance (from 2014) have been given to WP4 and WP5 that will use them in the tactical assessment of the ADAPT solution. Furthermore, as soon as the new data instance (2017) is ready, the EFPS model will be rerun and the results will be passed to WP4 and WP5, which is expected to happen in the first months of 2019.

6 Acronyms

Acronym	Definition
ACC	Area Control Center
AIRAC	Aeronautical Information Regulation And Control
ANSP	Air Navigation Service Provider
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
CRCO	Central Route Charging Office
DDR2	EUROCONTROL's Demand Data Repository
ECAC	European Civil Aviation Conference
ESFP	European Strategic Flight Planning
MTOW	Maximum Take-off Weight
SATA	Strategic Air Traffic Assignment
TW	Time Window

7 References

ADAPT, 2018. *D2.1 Support to modelling activities,* s.l.: s.n.

Bolic, T., Castelli, L., Corolli, L. & Rigonat, D., 2017. Reducing ATFM delays through strategic flight planning. *Transportation Research Part E: Logistics and Transportation Review,* pp. 42-59.

Castelli, L., Corolli, L. & Lulli, G., 2011. Critical Flights Detected with Time Windows. *Transportation Research Record (TRR), Journal of the Transportation Research Board,* Volume 2214, pp. 103-110.

Cook, A. & Tanner, G., 2015. *European airline delay cost reference values - updated and extended values (Version 4.1),* s.l.: s.n.

EUROCONTROL, CRCO, 2015. *Eurocontrol Route Charges Sytem.* [Online] Available at: http://www.eurocontrol.int/sites/default/files/content/documents/route-charges/information-circulars/circ2015-01-ectl-route-charges-system.pdf
[Accessed October 2015].

EUROCONTROL, 2017. *Annual network operations report, 2016.* [Online] Available at: http://www.eurocontrol.int/sites/default/files/publication/files/nm-annual-network-operations-report-2016-main-report-for-consultation.pdf
[Accessed May 2017].

Appendix A Turnaround constraints

SATA model

Let *G* be set of pairs of flights (f’, f’’) that are connected, with turnaround time $g_{f',f''}$ where the superscript ’ denotes the first flight and ’’ the following flight. Then the turnaround constraint is:

$$\sum_{\substack{r' \in R_{o_{f'}}^{a_{f'}}, t' \in \mathrm{T}_{f'}^{r'}: \\ t' + l_{r'}^{n_{r'}} + g_{f',f''} \leq t''}} x_{r'}^{f'}(t') \geq x_{r''}^{f''}(t''), \qquad \forall\, (f', f'') \in G, r'' \in R_{o_{f''}}^{a_{f''}}, \; t'' \in \mathrm{T}_{f''}^{r''}$$

TW models

Let *G* be set of pairs of flights (f’, f’’) that are connected, with turnaround time $g_{f',f''}$ where the superscript ’ denotes the first flight and ’’ the following flight. Then the turnaround constraint is:

$$x_{f'}(t') + x_{f''}(t'') \leq 1, \forall (f', f'') \in \mathcal{G}, t' \in T_{f'}^{0}, t'' \in T_{f''}^{0} : t' + l_{r_{f'}}^{n_{f'}} + g_{f',f''} \geq t''$$

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