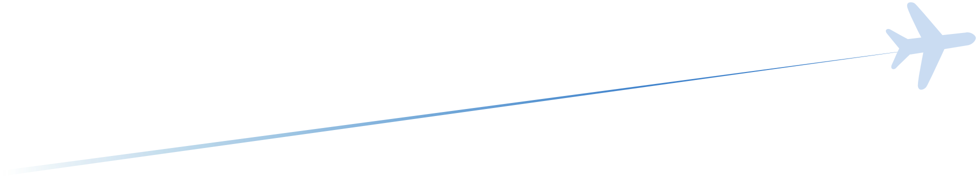

D2.1 Support to modelling activities

Deliverable 2.1

ADAPT

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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 presents the approach of ADAPT to the data management, describes the data sources considered, and the statistical analyses of the historical data, needed for the development of the data instance to be used for modelling efforts in the WP3, WP4, and WP5. Furthermore, the strategic and tactical assessment scenarios and the assessment indicators are defined.

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Executive summary

The scope of ADAPT is to propose a set of methods and tools (a solution) at the strategic and/or pre-tactical level of network management that is conducive to the trajectory-based operations, which clearly demonstrates the flexibility, information exchange responsibilities, and benefits for all the stakeholders. The aim of the ADAPT project is to adapt, create and test models and metrics that enable **strategic planning** (early information sharing), by providing the information on **flight flexibility** and **network hotspots**, which can eventually be integrated into the Network Operations Plan (NOP) and serve as a basis for stakeholder collaboration.

In order to develop the models and to assess them properly, a significant amount of different data is needed, based on the data requirements, coming from the modelling and assessment (validation) needs. The data that ADAPT will manage can be categorised as follows:

1. traffic and delay data (e.g. trajectories, causes and amounts of delay);
2. airspace environment data (e.g. airport and airspace capacity);
3. meteorological data;
4. cost data (e.g. flight cost data, and route charges).

Most of the datasets have already been acquired and loaded into the database. The database is already set-up, hosted by the University of Westminster. Secure access to the database by the ADAPT partners is also in place and all the partners working on the project have access to it.

The results of the analysis of historical traffic, regulations and airspace infrastructure data that was performed as initial steps for building the input for ADAPT models and subsequent assessments are presented. As the models are to be run on the busy day over the European network, first we selected a suitable (recent) test day. Then we describe the input data preparation process, and finish by reporting the results of the route clustering and regulations analysis. These results are the basis of the data instance that will be used in the modelling efforts in the WP3, WP4, and WP5.

1 Introduction

The scope of ADAPT is to propose a set of methods and tools (a solution) at the strategic and/or pre-tactical level of network management that is conducive to the trajectory-based operations, which clearly demonstrates the flexibility, information exchange responsibilities, and benefits for all the stakeholders. The aim of the ADAPT project is to adapt, create and test models and metrics that enable **strategic planning** (early information sharing), by providing the information on **flight flexibility** and **network hotspots**, which can eventually be integrated into the Network Operations Plan (NOP) and serve as a basis for stakeholder collaboration.

The ADAPT project consists of three main activities:

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

The ADAPT strategic solution development consists of three phases: (i) 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, (ii) the assessment of the expected economic loss in case unwanted events occurring (e.g., flight delays, bad weather), and (iii) the definition of some actions to mitigate expected demand and capacity imbalances, as detected in the two previous phases. Phases (i) and (ii) cover the definition of the ADAPT solution, while in phase (iii) the ESFP outputs are used to devise mitigation actions in order to improve the situation, if possible.

The ESFP model builds on two deterministic, integer programming models. The first model considers a busy day in the European network, and the changing sectorisation. Its aim is to assign a trajectory for each scheduled flight, in such a way that the nominal capacities of the network are respected (Bolic, Castelli, Corolli, & Rigonat, (2017), as results from the SATURN project (SATURN consortium, 2018)). When all flights have a trajectory (4D) and departure time assigned, these become inputs of a second integer programming model, the aim of which is to determine the flexibility (in terms of so-called Time Windows[1]) of all flights and the critical spots in the network. This second model uses departure times as the starting position of Time Windows (TWs), 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 (4D), assigned TWs and the hotspots in the network.

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[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.

Hotspots are expressed in two dimensions: location and time, that is to say as sector-hours (or airport-hours).

The ADAPT models (solution), will be assessed (validated) from the point of view of the goodness of applicability of such strategic/pre-tactical planning in tactical environment. In order to achieve this main objective, the ADAPT project will:

- Provide a thorough assessment (validation) of the ADAPT solution in the tactical setting, from two points of view:
    - Network-wide assessment, where simulations on the entire European network will be performed to help us in understanding whether the proposed TWs are meaningful from an operational point of view.
    - Flight-centric assessment, from a flight performance point of view where fuel consumption and arrival delay of individual flights are considered.
- Involve stakeholders into the development and refinement of the solution, metrics and assessment methodology.
- Define metrics in support of the development and assessment of ADAPT solution:
    - A (strategic) measure of the (economic) risk of hotspots, as a part of the ADAPT solution, to give information on how likely a hotspot identified strategically can be one on the day of operations, and what consequences it would bring
    - Statistically robust metrics on sector level (hotspots and “coldspots”) to be used in the assessment efforts, in order to compare the hotspots identified in the strategic phase with those that arise in the tactical phase.
- By working in close cooperation with stakeholders, develop requirements for the visualisation of the ADAPT solution results. The goal is to present the results in a way that is useful to the stakeholders.

In order to both develop and validate ADAPT models, extensive amounts of historical data are needed: on the network infrastructure, ATM status, traffic, costs, just to mention some. Figure 1 depicts the work breakdown structure in the project. WP3 develops the ADAPT strategic solution (EFPS mentioned above), whereas WP4 and WP5 take care of the tactical assessment, from a flight-centric point of view and network-wide view, respectively.

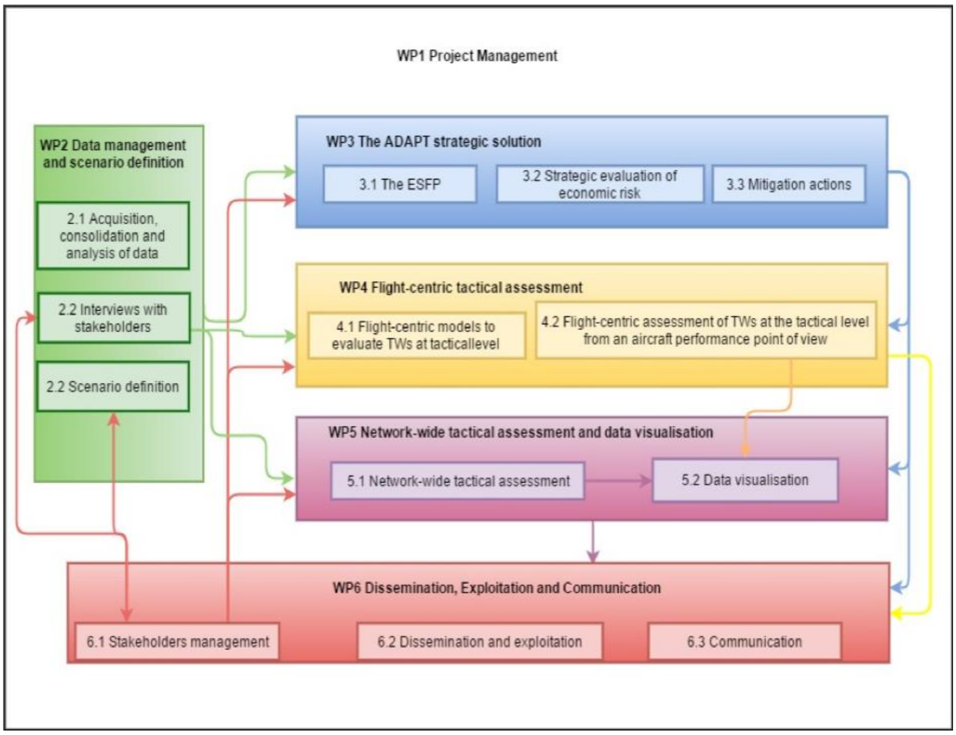

Figure 1. ADAPT work breakdown structure

The ADAPT model development and subsequent assessments have slightly different data needs. Even though most of the data (e.g., trajectory, traffic demand, airspace infrastructure) will be common to all, tactical assessments will need to consider some of the tactical level uncertainties, like weather forecasts, or regulations, or tactical costs (differ from strategic costs).

The tactical flight-centric assessment looks into the validity of TWs in tactical operations – in other words assessing if and to what extent a flight can respect its assigned time window, and how that in turn impacts individual flight’s performance and costs. Thus, trajectories, and good performance models are needed. Further, the data on (tactical) disruptions are also needed, in particular meteorological data to compute the influence of wind on aircraft speed.

Finally, the tactical network-wide assessment focuses on the network-wide effects of time windows. The ADAPT strategic models do not consider deconfliction of trajectories, thus a network-wide view on how would the deconfliction and other tactical disturbances (e.g. regulations) influence the assigned time windows will also be performed.

2 Data sources, acquisition and elaboration

Based on the data requirements listed in the previous section, here we describe the data sources, acquisition strategy and needed elaboration of data in order to prepare the input data for modelling. The following data categories have been identified:

1. traffic and delay;
2. airspace environment;
3. meteorological data;
4. airport data;
5. cost data.

The sources, acquisition status and elaboration needs are further detailed for each of the categories in the following text. In order to elaborate the data, their raw form is loaded into the database. The database structure is described in Section 3.

2.1 Traffic and delay

Different sources are used and consulted in order to prepare the traffic data for ADAPT's model:

- EUROCONTROL's DDR2: flight demand and trajectories from the day chosen as a test day (see the description of the test day selection in section 4.1) are sourced from DDR2 data. The trajectories of interest are the last filed flight plans (m1), regulated flight plans (m2) and executed flight plans (m3). Besides the trajectories on the selected day of operations, ADAPT sources traffic data covering different AIRACs[2] (Aeronautical Information Regulation and Control), more specifically AIRACs 1702 and 1709 roughly covering February and September of 2017, to perform statistical analyses when required (for example for the trajectory options). The aircraft rotations for the selected test day will also be acquired from the DDR2 data.
- IFPS initial flight plans: ADAPT also has access to IFPS data (m0) for the September 2017. These data contain the initial flight plans submitted by airlines, providing information such as the

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[2] **AIRAC** stands for **A**eronautical **I**nformation **R**egulation **A**nd **C**ontrol and stems from Annex 15 of the *Chicago Convention* Aeronautical Information Services (AIS) document that defines a series of common dates and an associated standard aeronautical information publication procedure for states (ICAO, 2004). An AIRAC cycle is composed of 28 days starting always on a Thursday.

initial estimated off-block time (a good match with the scheduled departure time) and initial desired route (before reacting to congestion/uncertainty).

- Daily ATFCM summary data: contain detailed information on the regulations that were applied daily. These are obtained from Network Manager (NM) ATFCM statistics.
- CODA summary delay data: might be needed to analyse delay and enable realistic delay generation for the assessments (for all the delays not caused by the ATFM actions).
- CODA taxi times: standard taxi times, published by CODA, are useful to model the time between gate and runway and from the runway to the stand.
- BADA performance models: finally, in order to model fuel consumption, ADAPT will use BADA 4.2 performance from EUROCONTROL. The consortium members have access to BADA 4.2.

2.2 Airspace environment

- EUROCONTROL's DDR2: the DDR2 repository also contains information regarding the airspace environment in terms of sector shapes, sector activations, sector and airport capacities, and basic information on ATFCM regulations.

2.3 Meteorological data

- The meteorological data are sourced from the ECMWF (European Centre for Medium-Range Weather Forecasts), and represent the wind forecasts. These weather forecasts have a lead time of 6 hours till 15 days ahead, with a resolution of 12 hours. For each sample, the North and East component of the wind, as well as the temperature are available on a geographic grid as a function of the pressure level. For the ensemble models, a total of 50 ensemble members are available. Each ensemble is created by running the weather forecasting models of ECMWF member states, with slightly perturbed initial conditions. The spread in the final forecast can be used as a measure of the uncertainty in the weather forecast.

2.4 Airport data

- Data coming from EUROCONTROL (Airport Corner) on the capacities of airports. The data contain maximum number of movements, terminal capacity, infrastructure of the airport and so on.
- Airport capacities as defined by the airport coordinators for the Level 3 slot-controlled airports, where available. Most of the airport coordinators publish the so-called coordination parameters on their websites.

2.5 Cost data

- Cost of delay: cost of delay models developed in-house by the University of Westminster (Cook & Tanner, 2015) will be revised for 2017. As this particular update of costs is not a part of ADAPT project, this revision may be based on inflationary changes rather than a more in-depth recalculation of the reference values, except for fuel costs, which will be explicit.

- Cost of ANS provision, which are needed to properly calculate route charges that are a part of the flight operations costs:
    - Central Route Charge Office (CRCO) unit rates in effect on the selected test day.
    - Oceanic rates as they differ from regular unit rates.
    - Unit rates of countries neighbouring CRCO ones, where available (e.g., usually available on the website of the state's ANSP).

2.6 Summary of data sources

Table 1. Summary of data sources

Category	Datasets	Acquisition status	Elaboration status as of November 2018
Traffic and delay	• DDR2 • DDR2 airspace infrastructure • IFPS initial flight plans • ATFCM summary data • CODA summary delay data • CODA taxi times • BADA performance models	• DDR2 traffic data available to consortium for different AIRACs • DDR2 airspace infrastructure available to consortium for different AIRACs • IFPS data available for September 2017 • ATFCM summary data available for 2016, 2017 and 2018 • CODA summary delay data yet to be acquired for September 2017 • CODA taxi times available for the summer season 2017 • BADA - ADAPT partners in possession of BADA licenses	All AIRAC 1702 and 1709 data is loaded in the database (database structure is described in the next section). IFPS data loaded into database. ATFCM data to be loaded.
Meteorological data	• Wind forecast ensembles	• EMCWF wind ensemble forecast available to consortium members, as wind ensembles 2017 is open access from ECMWF and can be accessed by any of the consortium members at https://www.ecmwf.int	Data in possession of TUD, will not be loaded to the database as are too large and needed only by TUD.
Airspace environment	• DDR2 files containing airport and airspace capacity	• DDR2 airspace environment data available to consortium for different AIRACs	Data loaded into the database.
Cost data	• Cost of delay • CRCO unit rates • Oceanic unit rates • Neighbouring states' unit rates	• Available in-house (University of Westminster) • Unit rates available for 2016, 2017, 2018 • In the process of acquisition • In the process of acquisition	Cost of delay needs an update (mostly on the cost of fuel). Unit rate data needs to be uploaded into database.

3 Database infrastructure

All data used in the ADAPT project are centralised in a single, secure database hosted at the University of Westminster.

3.1 Database access

Due to the various Non-Disclosure Agreements (NDAs) signed by the partners for the data access to the database needs to be properly secured. UoW has set-up a database on a virtual machine inside the University cluster, with access password-protected and encrypted with an SSL certificate.

Once logged-in, partners have permission to use the database resources for testing and production. The UoW cluster gives access to easy parallelisation, using more than twenty Central Processing Unit (CPU) nodes and a few Graphical Processing Unit (GPU) nodes too. They are well designed for the kind of mid-range computations that we will require during the production phase of ADAPT.

Access to data by the different partners is limited considering the different data requirements by the different institutions and subject to having the adequate licencing agreements. The control of data access ensures that possible data corruption is minimised. For instance, UNITS have full writing and reading access to the data, since they are coordinators, while other partners involved in the modelling have read-only access, or can create new tables but not erase any.

3.2 Database structure

The database itself is a MySQL database. MySQL is an open source standard for relational databases all around the world. It is well documented, reliable, and well suited for mid-range databases.

ADAPT uses the database for two purposes:

- To have standard input data with easy access.
- To store the results of the model(s) in an efficient way.

The structure of the database should be compatible with the following requirements of the models:

- Reproducibility: getting the same output from the same input with the same code.
- Reliability: making sure that the input data has not changed between two runs of the model.
- Consistency: making sure that the input in particular is self-consistent.
- Traceability: making sure that the output data can be linked unambiguously to a given input dataset.

Building-up on data management experience from past projects, ADAPT will thus use three different types of tables/schemas:

- Some schemas for the primary data, which should never be modified. This includes the DDR2 data for instance and other sourced data (see previous section).
- Some tables/schemas for the secondary data, which are built ‘off-line’ by some pre-processing codes of the models. These data change with the maturity of the models, and should be versioned.
- Some tables/schemas for the output data, which are the results of the models. Once again, these data change during the project, and should be versioned.

By versioning the secondary data and output data, the project ensures the traceability of the results. While the primary data are in their schemas in the database, all the direct input and output of the model will be centralised in the same schema, called *adapt_environment* in the database. Note that this schema is used as a placeholder for quite unstructured data, without enforcing the inner consistency of the data via formal relationships. The consistency of the input data is ensured upstream by the pre-processing tools, which should run different tests to this aim.

4 Historical data analysis

In this section we report on the analysis of historical traffic, regulations and airspace infrastructure data that was performed as initial steps for building the input for ADAPT models and subsequent assessments. As the models are to be run on the busy day over the European network, first we selected a suitable (recent) test day. Then we describe the input data preparation process, and finish by reporting the results of the route clustering and regulations analysis.

4.1 Test day selection

We have targeted a busy, but not unduly disrupted day in September 2017. Note that Fridays have been selected as they are usually busiest days of the week. In addition to a French Air Traffic Control (ATC) strike, many days were disrupted by various airline strikes/problems. Ryanair was particularly affected, with nearly a thousand cancellations over the month. There are likely to be other disruptions we are not aware of.

Table 1 lists the data fields used in the choice of the test day. As can be seen, quite a few dates are ranked high (in terms of traffic) at the yearly level. Apart from the number of flights, total ATFM delay, divided by cause has been considered, together with other causes not taken up by the ATFM actions (e.g. some of Ryanair disruptions). In summary:

- 1st choice: Friday 01 September 2017;
    - Ranked #3 in September 2017;
    - Ranked #5 in 2017;
    - Total ATFM delay quite high (but lower than 2nd choice);
- 2nd choice: Friday 08 September 2017;
    - Ranked #1 in September 2017;
    - Ranked #2 in 2017;
    - Total ATFM delay quite high, with a significant portion of weather-related delay. On top, there was also Thomas Cook strike that had a minor impact.

Table 2. September 2017 traffic summary

Rank (month)	Rank (year)	Date	Total flights	Total ATFM delay minutes	Total ATFM strike delay minutes	Total non-ATFM strike delay mins	Total ATFM weather delay mins	Comments
1	2	Fri 08SEP17	37 073	80 611	0	0	29 406	Thomas Cook strike (minor) **2nd choice for test day**
2	3	Thu 07SEP17	36 881	51 601	0	0	7 865	
3	5	Fri 01SEP17	36 798	66 991	0	0	16 419	**1st choice for test day**
4	6	Fri 15SEP17	36 792	90 136	0	0	25 907	Ryanair disruption (number of cancellations unknown)
5	13	Thu 14SEP17	36 313	88 998	0	333	26 492	Ryanair disruption (number of cancellations unknown)
6	16	Mon 04SEP17	36 209	52 571	0	0	12 029	
7	17	Fri 22SEP17	36 193	67 645	0	0	23 541	Ryanair disruption (50 flights cancelled)
8	20	Fri 29SEP17	36 068	78 190	0	0	18 955	Ryanair disruption (56 flights cancelled)
9	27	Wed 06SEP17	35 872	38 003	0	0	7 836	
10	33	Mon 11SEP17	35 681	102 209	19 195	0	32 383	French ATC strike
11	37	Thu 21SEP17	35 595	72 593	15 902	0	6 568	French ATC strike; Ryanair disruption (82 flights cancelled)
12	40	Thu 28SEP17	35 531	46 870	0	0	2 264	Ryanair disruption (48 flights cancelled)
13	42	Tue 05SEP17	35 518	20 146	0	0	144	
14	43	Mon 18SEP17	35 456	70 196	0	0	25 895	Ryanair disruption (65 flights cancelled)

Rank (month)	Rank (year)	Date	Total flights	Total ATFM delay minutes	Total ATFM strike delay minutes	Total non-ATFM strike delay mins	Total ATFM weather delay mins	Comments
15	50	Wed 13SEP17	35 246	99 841	140	0	52 712	French ATC strike; Ryanair disruption (number of cancellations unknown)
16	55	Wed 20SEP17	35 078	40 942	0	0	2 672	Ryanair disruption (64 flights cancelled)
17	56	Mon 25SEP17	35 064	46 254	0	0	14 460	Ryanair disruption (50 flights cancelled)
18	68	Tue 19SEP17	34 712	57 265	0	0	27 895	Ryanair disruption (62 flights cancelled)
19	72	Tue 12SEP17	34 620	188 051	92 803	196	13 123	French ATC strike; Air Berlin disruption (70 flights cancelled); Ryanair disruption (219 flights cancelled)
20	73	Wed 27SEP17	34 594	57 425	0	0	27 090	Ryanair disruption (38 flights cancelled)
21	81	Tue 26SEP17	34 242	44 897	0	0	15 618	Ryanair disruption (44 flights cancelled)
22	83	Sun 03SEP17	34 211	67 864	0	0	7 783	
23	93	Sun 10SEP17	33 814	103 490	0	0	32 291	
24	105	Sun 17SEP17	33 377	70 217	0	0	25 687	Ryanair disruption (80 flights cancelled)
25	114	Sun 24SEP17	33 143	71 900	0	0	13 781	Ryanair disruption (50 flights cancelled)
26	145	Sat 02SEP17	32 092	80 541	0	0	19 964	
27	156	Sat 09SEP17	31 701	108 664	0	0	35 151	
28	164	Sat 16SEP17	31 163	68 026	0	0	13 673	Ryanair disruption (80 flights cancelled)
29	171	Sat 23SEP17	30 896	53 660	0	0	3 965	Thomas Cook strike; Ryanair disruption (50 flights cancelled)
30	186	Sat 30SEP17	29 966	64 335	0	0	10 973	Ryanair disruption (52 flights cancelled)

Sources: NM ATFCM statistics (delays); DDR2 (number of flights)

4.2 Input data preparation

The ADAPT models, and the subsequent tactical assessment will be 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 will be taken from the report by Cook and Tanner (2015), with slight adjustments for inflation and the update of fuel costs.

4.2.1 Flights

The date chosen for creation of the input data is September 1st 2017 (see Section 4.1). Military flights, overflights, helicopters, and flights departing from and arriving at the same airport will be excluded, which will reduce the number of flights viable for the model from the 35 483 that flew on the chosen test day.

4.2.2 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 ADAPT models apply changing sector configurations, and here, for the baseline and the solution scenarios we will apply the configuration in place in Europe on September 1st 2017. Slightly different configurations will be applied in the mitigation scenario, depending on the location of saturated sector-hours (so called hotspots) coming out of the solution scenario results. The network consists of 204 airports and 1346 sectors (this is the total number of different sectors that were open at some point on the test day, they are not all open/active at the same time).

Furthermore, capacity information is needed to define the capacity constraints for airports and active sectors. DDR2 data contain information on airport and sector nominal capacities, which will be included in our input data as well.

4.2.3 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 for 15 of the most commonly used aircraft in Europe. Three 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 DDR2 *.mwc data file. The file contains the MTOW in metric tonnes for each aircraft type appearing in the AIRAC cycle.

4.2.4 Airline types and cost profiles

Airlines operating the flights included in the input data 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:

- 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 23 European Civil Aviation Conference (ECAC) airports (excluding the two non-ECAC Moscow airports) with over 25 000 000 passengers in 2017. The cost profiles are used to define flight costs to be used in the ADAPT models.

4.2.5 Routes and departure times

Only routes differing significantly from one another in terms of geographical distance (specifically, more than 30 kilometres 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 pair from the tens available to a few routes per combination. For more details on the route clustering and its results, see section 4.3.

As the ADAPT models are strategic/pre-tactical, we are interested in planning that refers to the strategically/pre-tactically known information, which is a scheduled departure time. The information available to us that is closest to the scheduled departure time is contained in the IFPS data (m0) files. Section 4.4 reports on the analysis of the m0 and m1 files and the decision taken regarding the sourcing of departure times for the ADAPT models input data.

4.2.6 Route charges and unit rates

Unit rates for September 2017 for all States signatories of the Multilateral Agreement relating to Route Charges (EUROCONTROL Central Route Charges Office, 2015) are taken from DDR2 CRCO route charges files (which are the same as the ones that can be found on the CRCO's website). Where available the route charges for States neighbouring CRCO signatories will also be included.

4.3 Route clustering

In order to create the routing options necessary for the application of the ESFP model, we proceeded with the route clustering of the trajectories that were flown in the period of 1702 (February) and 1709 (August/September) AIRACs. The two AIRACs were chosen to account for possible seasonal differences in the trajectory choices.

On the chosen test day (1 September 2017), there were 35 483 flights that flew between 14 484 Origin-Destination (OD) pairs. Thus, only OD pairs present in the test day are taken into account, resulting in 1 284 560 flights being eligible for route clustering. These flights were further filtered to exclude:

- Military flights
- Flights with origin or destination airports being "ZZZZ" or "AFIL"
- Training flights (same origin and destination)

- Oceanic flights on all other days but the ones on 1 September 2018. The reason being that over two months, having oceanic routes change twice a day (based on the wind changes), we would end up with too many route options, many of which could never be present as viable options on the same day.

For the remaining flights, the m1 trajectories were transformed into a geometry format, to speed up the clustering algorithm. For each OD pair, the Hausdorff distance[3] was calculated between all the trajectories belonging to the pair. Clustering was performed using the DBSCAN algorithm. DBSCAN clusters elements that are closely packed together, i.e., elements in a ε-neighbourhood and surrounded by a minimum number of neighbours. It requires two parameters: the maximum radius of the neighbourhood ε and the minimum number of elements *m* required for a cluster. It is important to note that DBSCAN does not require to be initialized with the number of clusters to create, but it autonomously finds the number of clusters suitable for the problem. This property fits our scenario since we cannot estimate the correct number of typical trajectories a priori. We set maximum radius of the neighbourhood ε = 0.3 (which corresponds to 30km) and minimum number of elements *m = 1* as parameters of the DBSCAN algorithm. Clustering was performed on a 64-bit Intel(R) Xeon(R) E5520 @ 2.27GHz quad core CPU computer with 16GB of RAM memory and Debian 8.0 operating system. The computation time was $\sim 12h$.

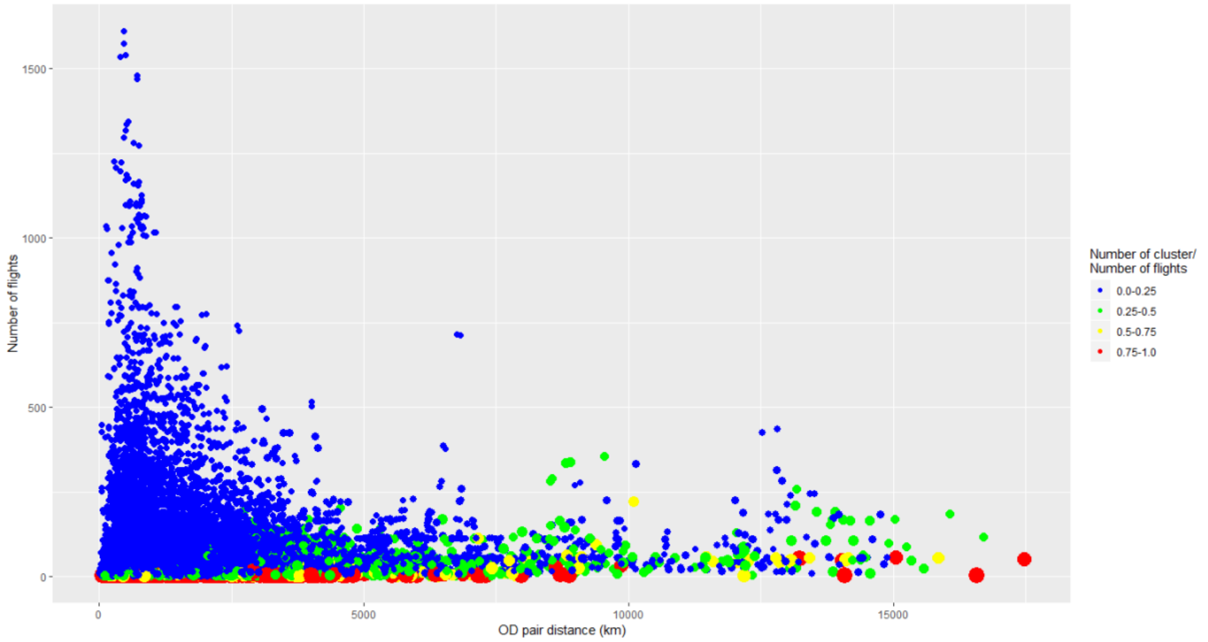

Figure 2. The cluster/number of flights ratio shown with respect to the number of flights and the distance between Origin and Destination

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[3] The Hausdorff distance is the maximum distance of a trajectory to the nearest measurement in the other trajectory.

Let us denote as Δ the ratio of number of clusters, over the number of flights (for each OD pair). Figure 2, shows the spread of Δ when plotted against the number of flights and the distance between Origin and Destination airports. The greater Δ, the bigger is the point representing it. As can be seen, the larger the distance between the OD airports, the lower the flight frequency and resulting Δ is higher. Low Δ values (blue dots) represent the low number of clusters resulting from relatively large number of flights – meaning that even though there were many flights between a certain OD pair within two AIRACs, most of those followed just a few trajectories.

Further point of interest is the distribution of the number of clusters across the OD pairs. Figure 3 shows the number of OD pairs versus the number of clusters. As can be seen, there are about 2500 OD pairs (corresponding to 17.6% of OD pairs) that have only one cluster. About 19% of the OD pairs have two clusters, and we can see that the number of OD pairs decreases with the increase of the number of clusters.

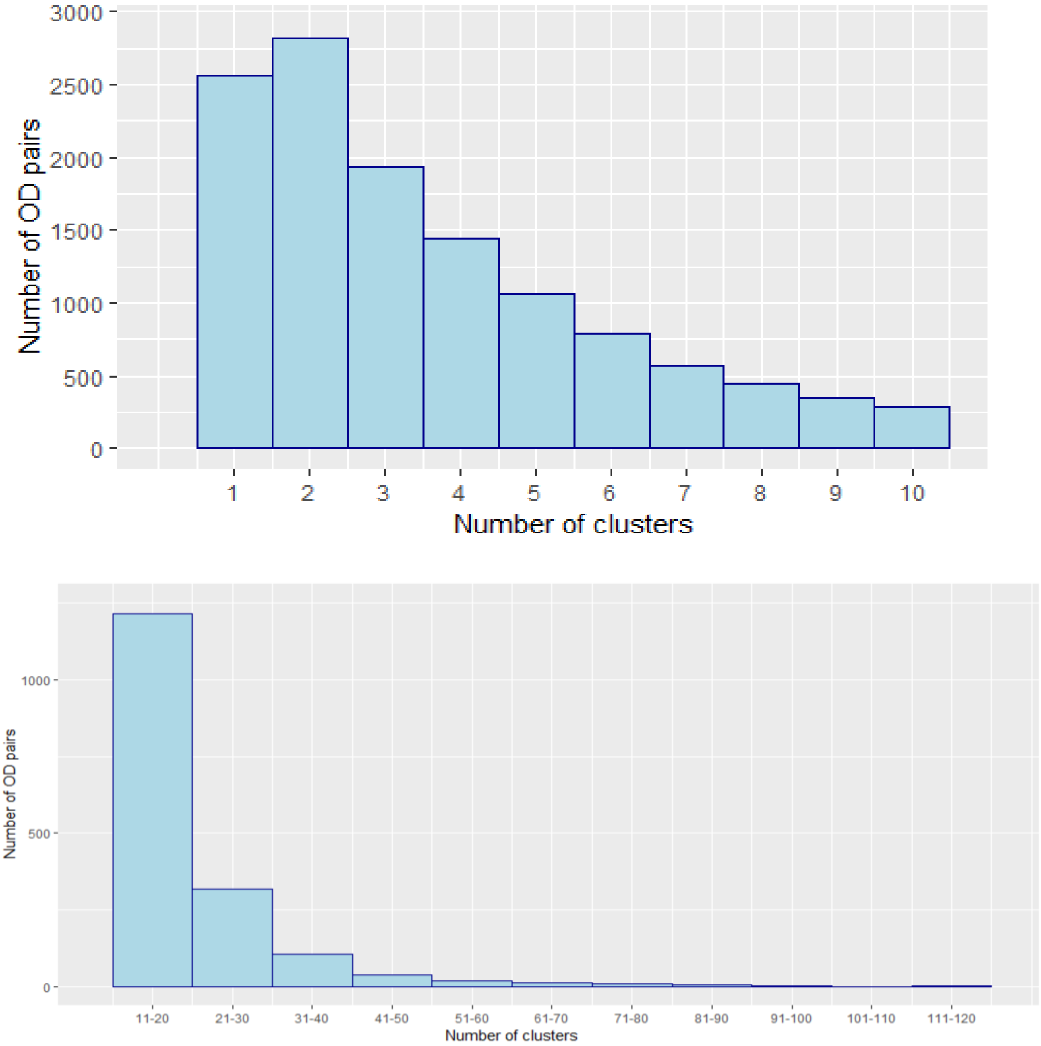

Figure 3. Distribution of the number of OD pairs versus the number of clusters

Most of the OD pairs with only one cluster are the ones with short flights. Figure 4 shows the resulting (one) cluster for the EBBR-LFRS OD pair. There were 105 flights flown in the two AIRACs used in the analysis, and all of them flew along the same route. Figure 5 depicts the case of an OD pair (EHAM-EGLL) with two clusters. There were 1003 flights over the analysed period and almost all followed the blue trajectory, while only two flights belong to the red cluster. This was probably due to weather or some other ATFM reason.

Figure 4. EBBR-LFRS pair with one cluster

Figure 5. EHAM-EGLL pair with 2 clusters

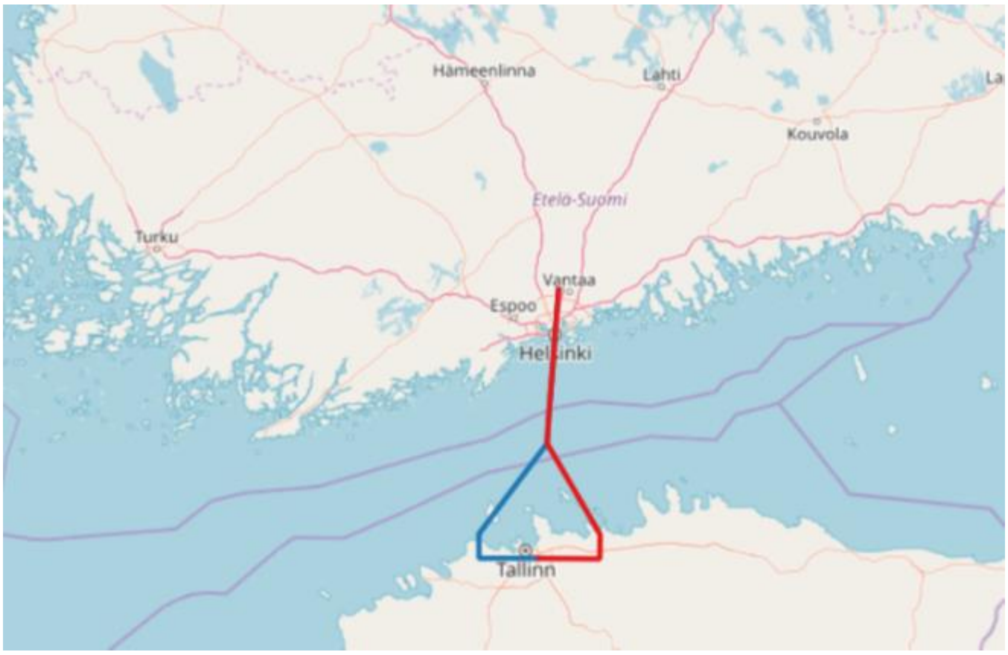

Figure 6. EFHK-EETN pair with two clusters

Figure 6 shows a different case of the 2-cluster OD pair that had 413 flights in total. Blue cluster is composed of 89 flights compared to the 324 flights in the red cluster, representing a more regular use of routes when compared to the situation depicted in Figure 5. The presence of two clusters is most likely due to the weather (wind) induced trajectory choice.

Next, we turn to the cases of multiple clusters, presented in Figure 7 and Figure 8. Both examples involve distant OD pairs. Figure 7 shows the LEMD-ZSPD pair that was traversed by 56 flights that were divided into 7 clusters. Similar situation is depicted in Figure 8 for EGSS-LGAV pair that contained 96 flights, divided into 7 clusters. All of the presented examples show that the longer the route, it is more likely the airlines would/could choose different trajectories.

Next step after the route clustering is the clustering along the OD pair-aircraft trajectory combinations, which will be used for the creation of the data instance for modelling in WP3.

Figure 7. LEMD-ZSPD pair with 7 clusters

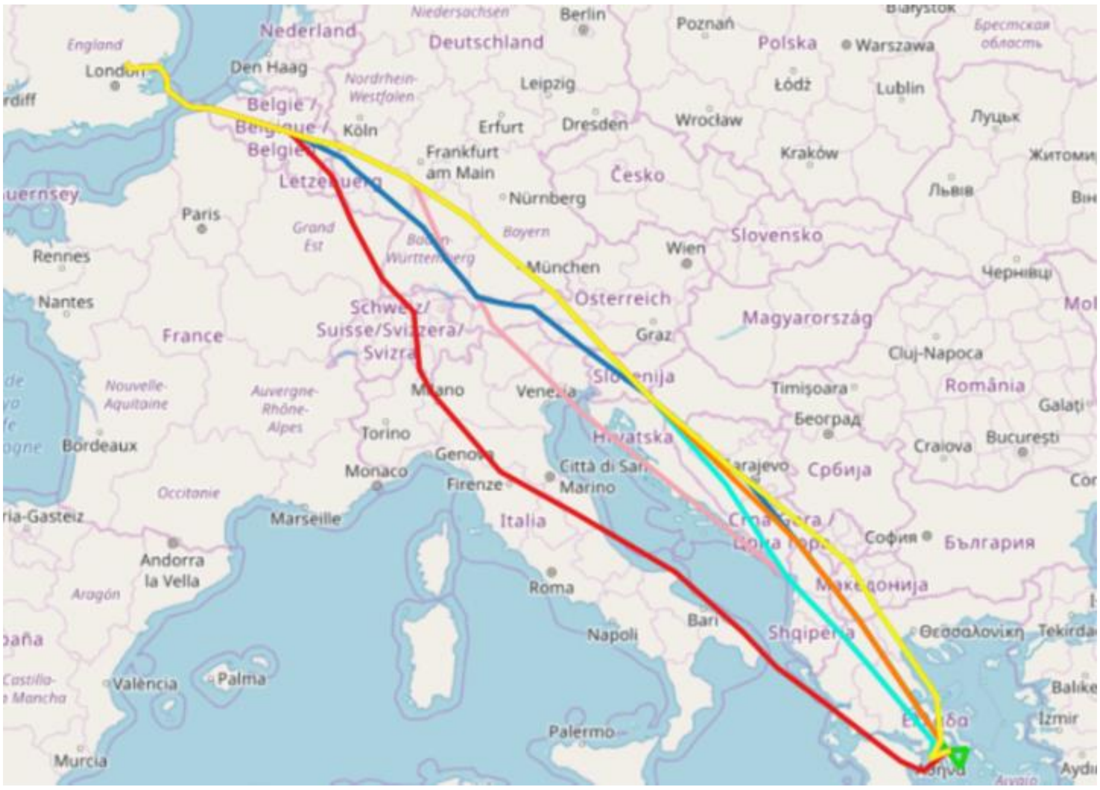

Figure 8. EGSS-LGAV pair with 7 clusters

4.4 Departure times

As ADAPT models are intended for strategic/pre-tactical use, the departure time used should be the scheduled departure time. However, we do not have access to the schedule data, but to the flight plan (FP) information, which, for various reasons, often differs from schedule.

As listed in the section 2, the consortium has access to the IFPS (m0) and DDR2 flight plans (m1-3):

- (m0) initial flight plan from IFPS database. The database contains all the FPs submitted by the airlines before the last filed FP. A new resubmission of a flight plan is done when any of the key parameters are changed.
- (m1)[4] the last filed flight plans,
- (m2) regulated flight plans, same as the last filed flight plan above, except for a single difference – regulated flights contain a constant time offset corresponding to the assigned ATFM delay.
- (m3) executed flight plans, corresponds to the last filed flight plan data updated with available radar information whenever a flight deviates from its last filed flight plan by more than any of the pre-determined thresholds of: five minutes, seven flight levels or 20 NM. The radar data feed is used to update m1 (and m2) to construct the actual trajectory is one minute. This trajectory represents the closest estimate available in official NEST data files of the flight trajectories actually handled by controllers on the day of operations.

As in the ADAPT we are interested in the earliest available information, we decided to look into the differences between the m0 and m1 flight plans. IFPS database contains the FP submitted by the airlines and updated each time a new FP is sent. Each flight plan submission contains a filing time and an Estimated Off-Block Time (EOBT).

The aim of this analysis was to assess the difference between the EOBTs of m0 and m1 flights and see if we can use the m0 EOBT data as the earliest indication of the requested departure time.

We analysed all the m0 and m1 data for the September 1st 2017, for which there were 35 483 flights that submitted the last flight plan. The first comparison shows that 32 387 flights (91.3%) of the total flights present in m1, have a correspondence in m0. The remaining flights submitted only one flight plan and thus do not appear in the m0.

About 20% of the flights present in the m0 submitted more than one flight plan, while others had only one flight plan in the m0. The EOBT times present in m0 and m1 were analysed in order to determine if there is difference, and the magnitude of said difference, to be able to decide which EOBT times should be used in the ADAPT strategic models as the “requested” departure times.

Let $D = EOBT(m1) - EOBT(m0)$.

The first part of the analysis focused on comparing the EOBT of the earliest flight plans submitted (as said above 20% of flights had multiple submissions) and part of m0, with the EOBT present in the m1. In this case we found that in 71% of the cases EOBT(m0)=EOBT(m1), meaning that in 29% of the cases the EOBTs differ.

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[4] In case there was only one flight plan submitted, that will be included in the DDR2 data as m1, and will not be a part of the IFPS’s m0 plans.

The average difference (where present) $\mu(D)$ is 36 minutes, with standard deviation, $\sigma(D)$, of 48 minutes. Figure 9 depicts the distribution of D across the number of flights. As can be seen from the figure, the later flight plan may result in the earlier EOBT, which happens in 12% of the cases.

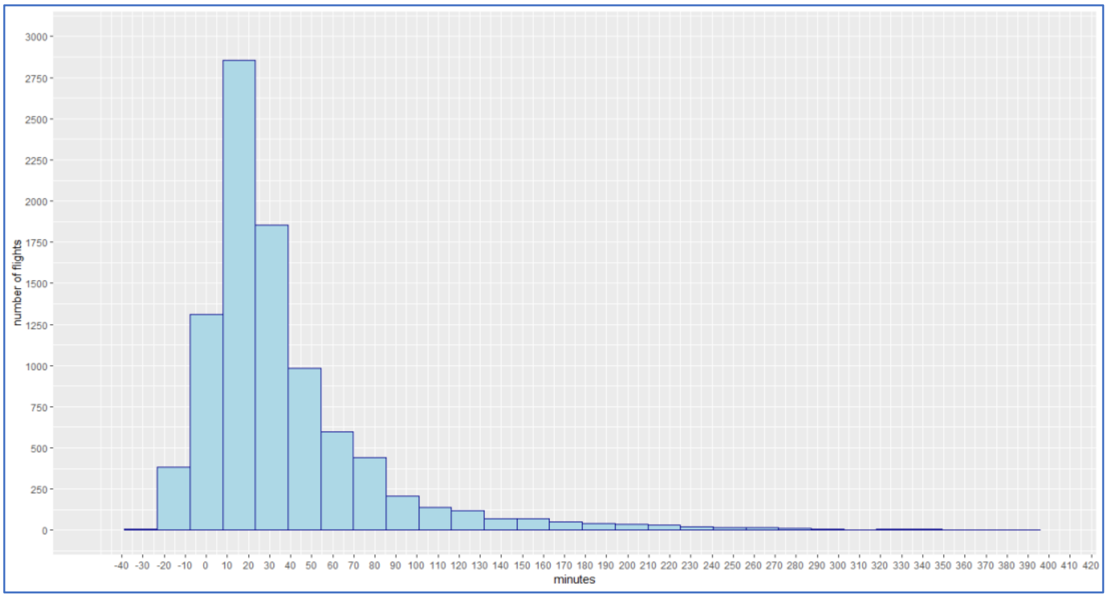


Figure 9. Distribution of difference in EOBT times (EOBT(m1)-EOBT(m0)), for flights with different EOBTs, first flight plan in m0

The second part of the analysis focused on comparing the EOBT of the latest flight plans submitted that are a part of m0, with the EOBT present in the m1. In this case we found that in 73% of the cases EOBT(m0)=EOBT(m1), meaning that in 27% of the cases the EOBTs differ. The average difference $\mu(D)$ is 34 minutes, with standard deviation, $\sigma(D)$, of 46 minutes. Figure 10 depicts the distribution of D across the number of flights in this second case. As can be seen from the figure, the later flight plan (m1) may result in the earlier EOBT, which happens in 13% of the cases.

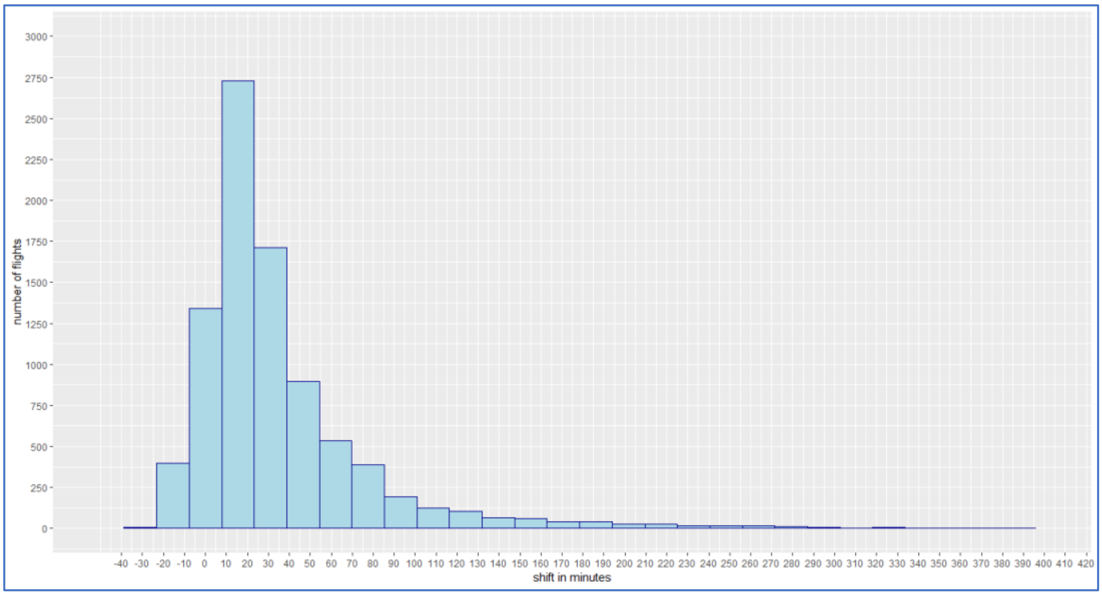


Figure 10. Distribution of difference in EOBT times (EOBT(m1)-EOBT(m0)), for flights with different EOBTs, last flight plan in m0

As the ADAPT is aiming at improving the planning in strategic/pre-tactical environment, we are eager to use the earliest data available. As can be seen from this analysis, EOBTs contained in the m0 indeed differ from the ones present in the last filed flight plan (m1). There are more flights with the differing EOBT when we consider the first flight plan submitted. Thus, the consortium decided to take the EOBT of the first flight plan submitted as the “requested departure time” to be used as an input in the ADAPT models. Note that even though m0 is the earliest available flight plan information, it is far from being strategic, or even pre-tactical as on average the first flight plans are filed about 10 hours before the requested departure time.

4.5 ATFM regulations analyses

The data is sourced from the Daily ATFCM Summary files, obtained from the EUROCONTROL’s Network Manager (NM) ATFCM statistics website. The data covers 2016, 2017 and first 4 months of 2018. The daily summary reports contain ten different reports on the impact of regulations on different parts of the network or stakeholders, in varying levels of aggregation. For our purposes, only three reports are used:

1. Delay per Regulation: for each regulation in effect on the day, the following information is given: date of regulation, traffic volume set, regulation name, number of regulated flights, number of delayed flights, total delay (minutes), average delay per regulated flight (minute/flight), average delay per delayed flight (minute/flight).
2. Regulation Report: this report gives more information on the causes of regulations and their duration. The following information is given: date of regulation, traffic volume set, reference location (unique name of the sector or airport over which the regulation is imposed), traffic volume, regulation name, location type (airport or en route), regulation start time, regulation end time, cancel status (in case regulation was cancelled, the status is “Cancelled”), cancelled time (the time when the regulation was cancelled, could be even before the scheduled start

of the regulation), regulation duration (in minutes, can be negative in case the regulation has been cancelled before its scheduled start time), all regulated traffic (number of impacted flights), regulation reason description (contains one of the codes describing the cause of regulation), window width (in seconds), regulation description (further, free text regulation reason description)

3. Regulation Definition: more information on the regulation capacity is given. Contains: date of regulation, traffic volume set, regulation name, regulation start time, regulation end time, regulation rate (hourly capacity), pending rate.

The regulation data analyses were performed in order to learn more on the causes and location of regulations, over a long time period. From Table 3 can be seen that the number of regulations increased in 2017 with respect to 2016, bringing the increased of the total ATFM delay imposed on the flights. The number of network elements (sectors or airports) over which the regulations were imposed also increased in 2017. Results for 2018 are given more for illustrative purposes, as they comprise only 4 months of the year.

Table 3. Distribution of regulations across years, total delay incurred and number of network elements affected

Year	Number of regulations	Total Delay (min.)	Number of network elements
2016	33 295	15 522 014	1226
2017	39 114	15 841 041	1307
2018 (4 months)	8 579	3 178 362	705

The analysed data contain 80978 regulations, which are distributed over 1659 distinct network elements (airports or sectors). Figure 11 shows the distribution of the number of regulations that were assigned for airport or en route issues. As can be seen, airport regulations are about half of the number of en route regulations. What is more interesting is the fact that even though the airport regulations impact a significantly lower number of flights (730 396 compared to 1 166 501, see Table 4), they cause a higher amount of delay, on average: 20.3 minutes/flight for airport related regulations, and 16.9 minutes/flight for the en route ones.

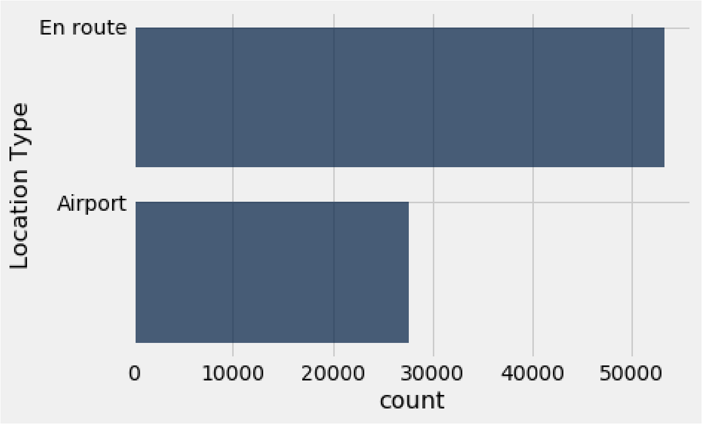


Figure 11. Distribution of the number of regulations over the location type (airport or en route)

Table 4. Number of delayed flights and total delay (in minutes), divided by regulation location type

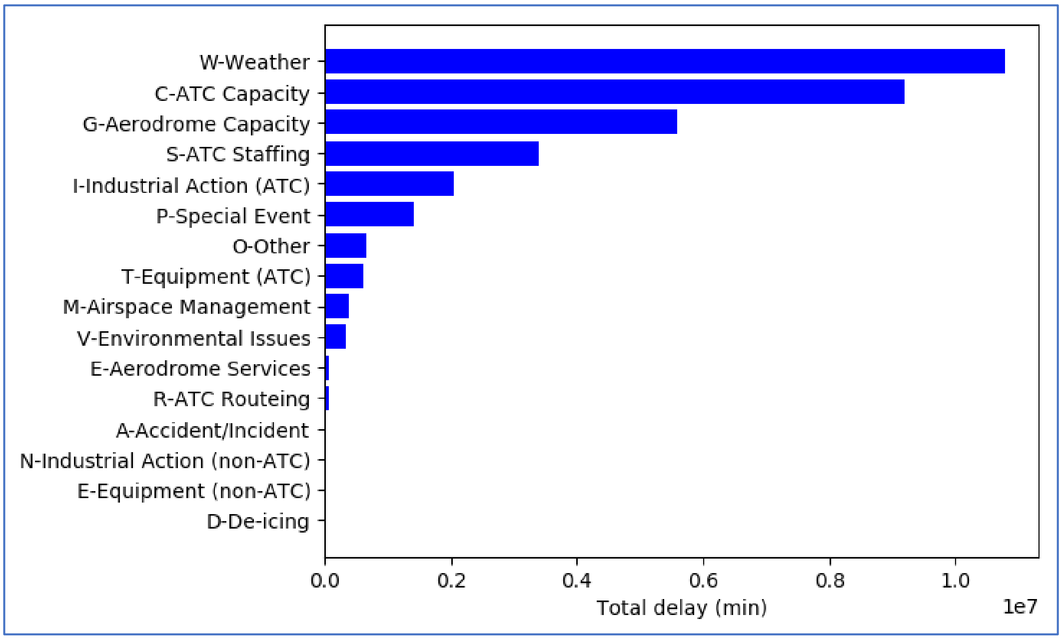
Location Type	Number of delayed flights	Total delay (minutes)
Airport	730 396	14 823 878
En route	1 166 501	19 717 539

Regulations are activated whenever there is a capacity-demand imbalance. The causes of the imbalances can differ, and currently are classified in 16 categories, so called regulation reasons (EUROCONTROL, 2018):

- W-Weather: can be applied either at Airport or En Route, when expected capacity is reduced due to any weather phenomena.
- C-ATC Capacity: can be applied either at Airport or En Route. En Route when demand exceeds or complexity reduces declared or expected ATC capacity, at an Airport when demand exceeds declared or expected ATC capacity.
- G-Aerodrome Capacity: applicable only at an Airport type location. “Reduction in declared or expected capacity due to the degradation or non-availability of infrastructure at an airport. e.g. Work in Progress, shortage of aircraft stands etc. Or when demand exceeds expected aerodrome capacity.”
- S-ATC Staffing: both Airport and En route. “Unplanned staff shortage reducing expected capacity.”
- I-Industrial Action (ATC): both Airport and En Route. “Reduction in any capacity due to industrial action by ATC staff”
- P-Special Event: both Airport and En route. “Reduction in planned, declared or expected capacity or when demand exceeds the above capacities as a result of a major sporting, governmental or social event. It may also be used for ATM system upgrades and transitions. Large multinational military exercises may also use this reason. This category should only be used with prior approval during the planning process.”

- O-Other: both Airport and En Route. “This should only be used in exceptional circumstances when no other category is sufficient. An explanatory ANM remark MUST be given to allow post ops analysis.
- T-Equipment (ATC): both Airport and En Route. “Reduction of expected or declared capacity due to the non-availability or degradation of equipment used to provide an ATC service.”
- M-Airspace Management: both Airport and En Route. “Reduction in declared or expected capacity following changes in airspace / route availability due to small scale military activity
- V-Environmental Issues: both Airport and En route. “Reduction in any capacity or when demand exceeds any capacity due to agreed local noise, runway usage or similar procedures. This category should only be used with prior agreement in the planning process.”
- E-Aerodrome Services: applicable to Airport type locations. “Reduced capacity due to the degradation or non-availability of support equipment at an airport e.g. Fire Service, De-icing / snow removal equipment or other ground handling equipment.”
- R-ATC Routeing: En Route only. “Network solutions / scenarios used to balance demand and capacity.”
- A-Accident/Incident: Airport only. “Reduction of expected ATC capacity due to an aircraft accident / incident.”
- N-Non-industrial Action (non-ATC): Airport only. “A reduction in expected / planned capacity due to industrial action by non ATC personnel.”
- D-De-icing

Figure 12 displays the total delay (blue, top graph) in minutes attributed to each regulation reason, as well as the total number of flights (orange, bottom graph) that were delayed. As can be seen, the major delay cause is weather (this is summed across both Airport and En Route locations), followed by the ATC capacity, Aerodrome capacity and ATC staffing. ATC union actions are the fifth largest cause of ATFM delay. The total delay is on the order of magnitude of millions of minutes for the period under analysis. Even though the weather causes the highest delays, the highest number of flights are delayed due to ATC capacity (bottom graph).



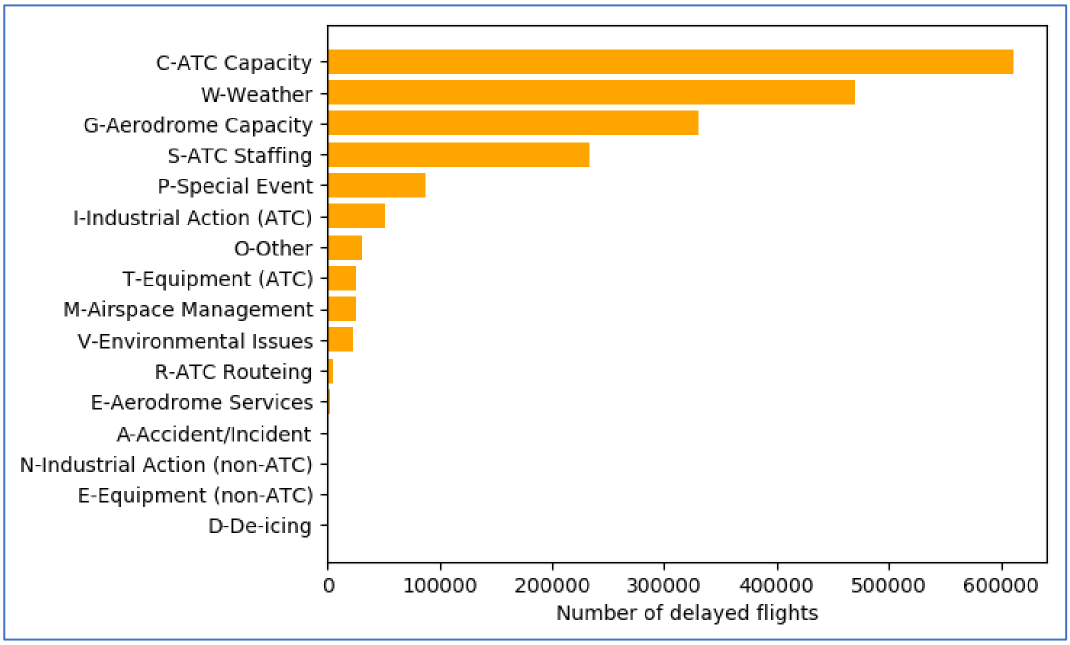


Figure 12. Total delay (minutes) and number of delayed flights, shown across different regulation reasons

Further analysis shows that when the regulation reason delays are further divided by location, a slightly different reason ranking is obtained. For the airport type locations, the highest amounts of delays are caused by weather, followed by aerodrome capacity, ATC capacity and environmental issues (see Figure 13). For en route locations the highest-ranking cause of delay is ATC capacity, followed by weather, ATC staffing and industrial action. Thus, both the location type and the regulation cause are important when considering the amount of delay (and the number of delayed flights).

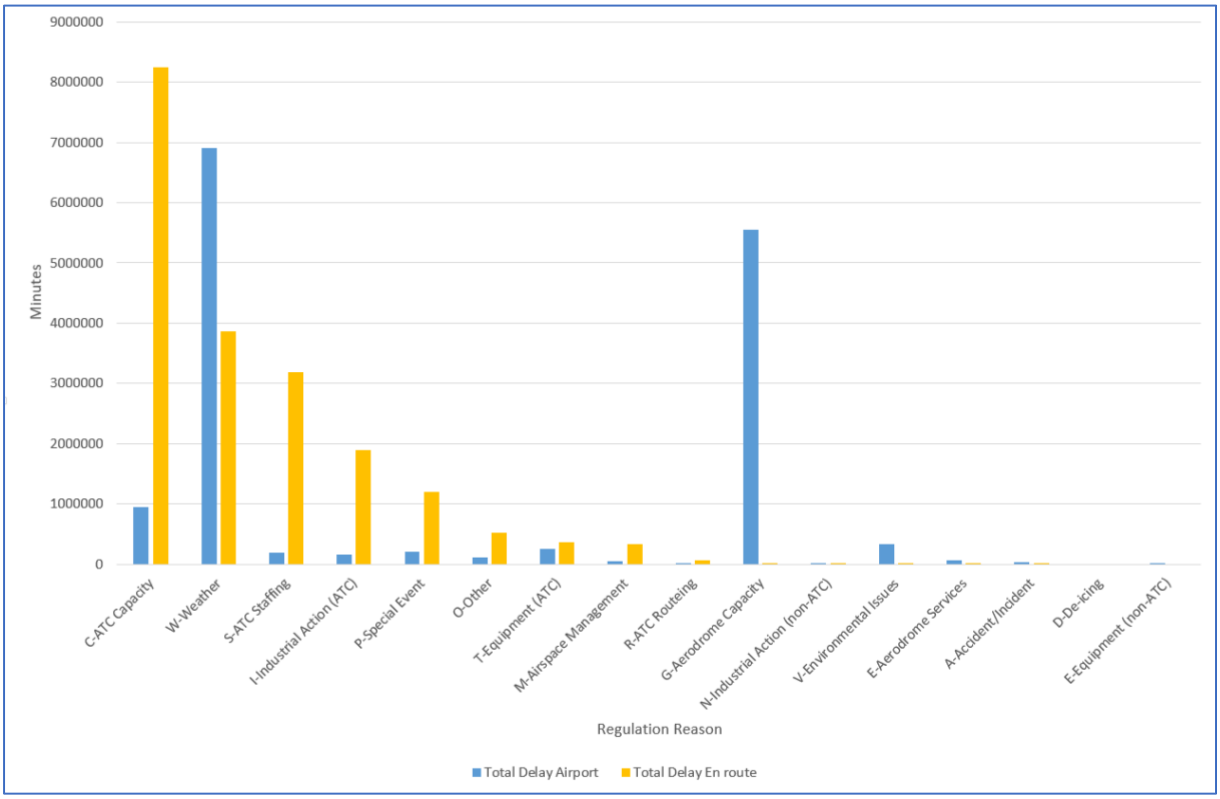


Figure 13. Amount of total delay (min.), shown across regulation reason categories and divided by location. Airport is shown in blue, and en route in yellow.

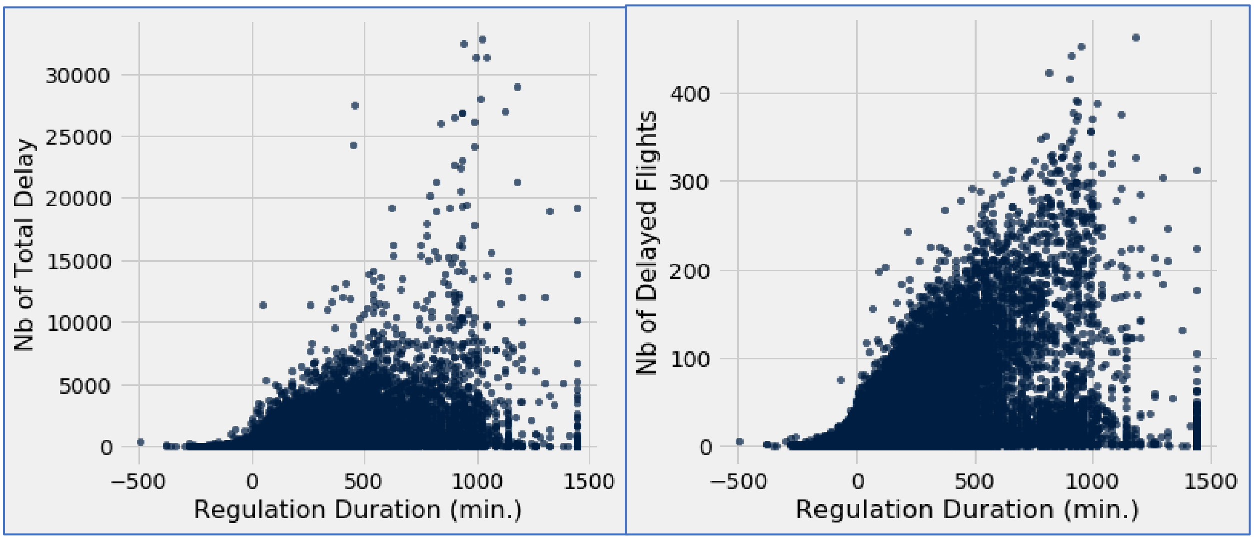


Figure 14. Relation between regulation duration (min.) and total delay (left), or number of delayed flights (right)

Another important characteristic of regulations is their duration. Figure 14 shows the relationship between the regulation duration and total delay accumulated by regulation (left), and between regulation duration and the number of delayed flights (right). The total delay increases with regulation duration, up till about 500 minutes of duration, and then even though there are instances where the delay increases with duration, most of the total delay remains below 10 000 minutes. The number of delayed flights demonstrates a bit stronger positive linear relationship with the regulation duration – the number of delayed flights increases with the duration. In the course of the project (Task 3.2: Strategic evaluation of the economic risk) we might decide to explore these relationships further in order to obtain more formal mathematical formulation. It is important to note that the regulation duration can be negative. When a regulation is cancelled before its scheduled start time, the regulation duration is negative. However, even a cancelled regulation can still impose delays on flights. For example, the regulation is scheduled to start at 10:00, and is cancelled at 9:00. A flight is scheduled to arrive after 10:00 at the regulated location and as such is subject to the ATFM delay, but is scheduled to leave at 8:00, an hour before the regulation is cancelled. As the ATFM delays are assigned before the departure, this flight will be assigned the ATFM delay and will be affected by the regulation even if the regulation is eventually cancelled.

4.5.1 Sample distributions of delay and regulation duration

As the aim of Task 3.2 is to quantitatively evaluate the (economic) risk associated with each sector and define its severity, we are interested in obtaining the characterisations of each location where regulations were applied. Table 5 lists the top 20 locations (airports or sectors) when sorted by the number of regulations that were imposed in the analysed period (2016-2018). The location with most regulations is Zurich airport LSZH, followed by Amsterdam airport, and the first nine locations had well over one regulation imposed per day, over the analysed period.

Table 5. Top 20 locations with highest regulation delay accumulated in the analysed period

Reference location	Count	Total delay (min.)	Number of delayed flights	Average number of regulations per day
LSZH	1 797	557 034	41 739	2,12
EHAM	1 567	1 636 254	82 633	1,85
LTBA	1 435	1 405 874	81 927	1,69
LTFJ	1 297	1 845 094	75 755	1,53
LFPO	1 132	460 803	25 554	1,34
LEBL	1 064	606 717	36 636	1,26
LLBG	1 004	241 587	10 934	1,18
LPPT	954	307 033	16 365	1,13
EDYYD5WH	910	292 993	22 686	1,07
EDYYB3EH	660	283 556	18 243	0,78
EGKK	621	844 635	35 437	0,73
EDUUFUL1U	573	224 127	18 903	0,68

Reference location	Count	Total delay (min.)	Number of delayed flights	Average number of regulations per day
LFRRMZU	557	119 133	9 027	0,66
EDYYD5WL	555	263 921	18 411	0,65
LEMD	552	243 527	13 070	0,65
LFRRQXSI	550	183 277	10 829	0,65
EDUUERL12	549	150 276	11 299	0,65
LFRRNU	539	137 574	8 654	0,64
LFRRMZSI	514	331 325	19 295	0,61
LGIR	512	154 259	8 457	0,60

For further analysis, we obtained a few characterisations for each location where regulations were applied. First, the distribution of the regulation duration for each regulated location is obtained, as well as the total opening time of the location (as a sector can be active for only a portion of a day, for more detailed explanation see section 4.5.2). Second, the distribution of average delay (per delayed flight) is calculated. The example of the analyses performed for each regulation location in the dataset are given below – an en route sector and an airport location.

Figure 15 shows the sample distribution (i.e. obtained from the data) – histogram - of the regulation duration and of the average delay per delayed flight for the EDYYD5WH sector. Most of the regulations lasted less than 200 minutes, and most of the average delay per flight is under 20 minutes per flight. An important note is that the regulations can be imposed on the sector only when that sector is active (open), which is another important piece of information. During the September of 2017, this particular sector was open for 25 703 minutes, 17 475 out of which it was under regulation (~68% of the time).

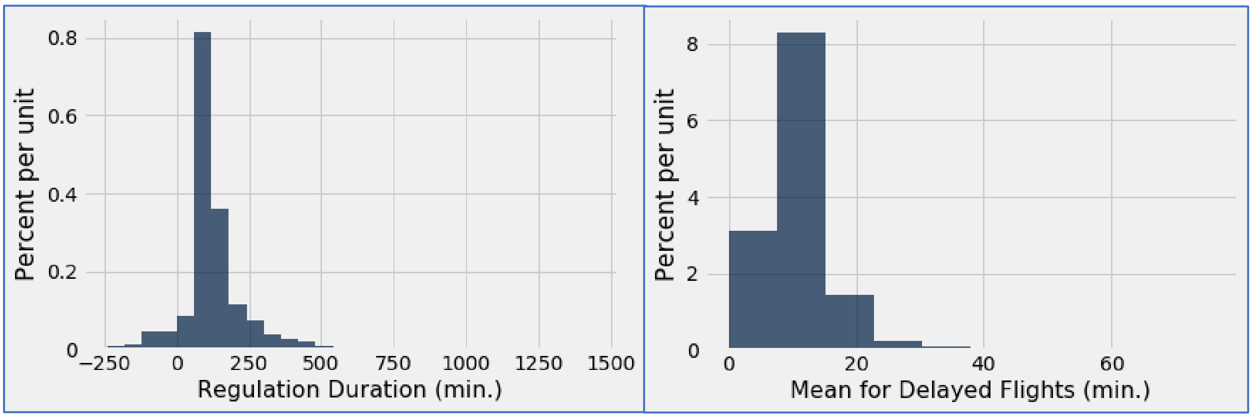


Figure 15. Histogram of regulation duration (left) and average delay (right) for EDYYD5WH sector

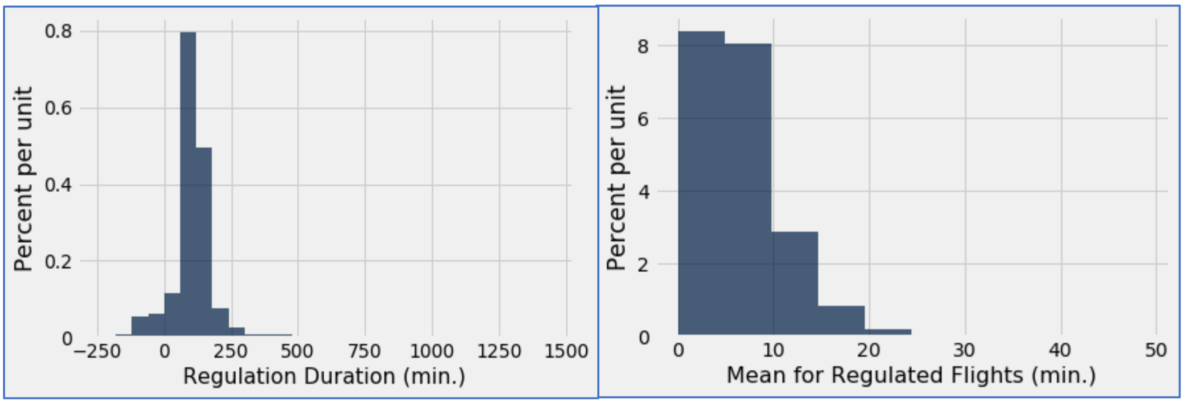


Figure 16. Histogram of regulation duration (left) and average delay (right) for LSZH airport

Figure 16 shows the histograms of regulation duration and of average delay for the LSZH airport. As can be seen, the distribution of regulation duration for this airport is similar to the distribution of the sector depicted in Figure 15. Conversely, the average delay distributions are rather different, showing that the LSZH regulations caused less delay per flight when compared to the same distribution for EDYYD5WH sector.

These characterisations are calculated (and stored) for each location that was under regulations during the period under analysis (2016-2018).

4.5.2 Available sector configurations

The DDR2 data contains two file types that report on the available configurations (*.cos extension) and the opening times of the configurations (*.cfg extension) in each AIRAC cycle. From these two files, we can find out which configurations and consequently sectors were open on each day, and for how long.

Knowing available configurations and the duration of their activation is important for the task 3.2 of the project (e-risk determination) and for the re-definition of configurations in mitigation scenarios (task 3.3).

For each AIRAC cycle in the period of 2016 – April 2018, the analysis of the available configurations and their actual openings has been performed and will be used together with the ATFM regulations analysis in order to determine the probability of regulation occurrence and the likelihood of incurring the economic consequences (i.e. delay) from it.

In the AIRAC 1709 (August 17th – September 13th 2017), 207 ACCs had listed 5646 available configurations. Out of these, 1301 configurations were active at some point in time. Active configurations were composed of 1346 distinct sectors.

4.5.3 Next steps

The analysis of the regulations shows that both the location type and the regulation cause are important when considering the amount of delay (and the number of delayed flights). Furthermore, the regulation duration also impacts the number of delayed flights and the amount of delay, which is further conditioned by the actual activation of the regulated location. The results of these preparatory analysis offer some insights that will be taken up in the task 3.2, where we will decide which relationships to explore further in order to obtain the reasonable measure of the economic risk.

5 Scenario definition

Several scenarios are needed on the ADAPT project as they first need to cover the scenarios for the application and assessment (mathematical verification) of ADAPT solution, and the strategic mitigation scenarios (capacity adjustment, pricing schemes). Further, the tactical impacts assessment (i.e. validation) scenarios are needed, that focus on the type of disturbances to introduce in the system in order to make the assessment more realistic, and to be able to draw robust conclusions (e.g. delay probability distribution, weather impact, regulations, to mention some).

In order to capture this, ADAPT will make use of relevant assessment metrics, defined together with the scenarios. Following sections describe the baseline, solution, mitigation and tactical assessment scenarios, and list the metrics to be used in the various assessments.

5.1 ADAPT baseline and solution 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, the earliest traffic data we have access to are the first filed flight plans (m0), which are also rather tactical, as they are filed on average 10 hours before the flight. Furthermore, the trajectory data in m1 flight plans (last filed, and as such very tactical) describes better the intended trajectory than the m0. Thus, in our analysis, we take the departure times from m0, and the trajectory from m1. As such, these data (m1) take into account perturbations and ensuing regulations that are not known in the strategic phase. Both m0 and m1 files are not suitable to be used for baseline scenario: m0 because the trajectory information is rather limited and it is still on average filed just a few hours earlier than the last filed flight plan; m1 because it already takes into account some factors that are usually not known in the strategic phase. Furthermore, today the strategic planning is not really applied, making it impossible to compare the possible strategic solution with the current, more tactical situation. Thus, a suitable baseline and solution scenarios need to be created.

5.1.1 Baseline scenario

A more suitable baseline scenario is obtained by applying the strategic model, with unconstrained capacities, which is consistent with the current practice of not considering capacity in the strategic phase. Baseline scenario de facto corresponds to a simple assignment of routes of minimum cost (or minimum duration), disregarding capacities.

Thus, the baseline scenario assigns minimum cost routes (from a set of possible routes) to flights, at the requested departure times. Some arrival shift is possible (if the chosen route is longer than the shortest duration route). As the capacities are not enforced, the second (TW) model cannot be applied (as in this case the TWs would be either infinitely large, or of the maximum allowed duration). Thus, the measure of flexibility cannot be obtained in the baseline scenario, which is also consistent with the current situation.

5.1.2 Solution scenario

Solution scenario consists of the application of the ADAPT solution (European Strategic Flight Planning Model ESFP) on the created data instance. The ESFP consists of two deterministic integer programming models. The first model assigns a trajectory for each scheduled flight, in such a way that the nominal capacities of the network are respected – thus, the trajectories and the opening times of TWs are determined and are in turn the input into the second integer programming model. The objective of the second model 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 in the network.

5.2 ADAPT mitigation scenarios

Using this information, actions at the strategic level to mitigate the hotspot severity can be taken. ADAPT proposes two paths to mitigation: by suggesting new airspace configurations (Task 3.3.1), or redistributing traffic by modifying the en route charging mechanisms (Task 3.3.2). Updated sets of trajectories, associated TWs, and potential hotspots will be produced to be given as inputs to WP4 and WP5.

5.2.1 Capacity mitigation

For example, if the hotspot is linked with the high economic risk, an alternative sector configuration (from historic configurations provided by Task 2.1.2, and described here in section 4.5.2) that provides higher capacity might be opened earlier (or later) in the day to alleviate the problem. Thus, the ESFP model is run again, with the new configuration as an input, resulting in an updated set of flight plans, TWs, and hotspots.

We foresee the following capacity mitigation scenarios:

1. Capacity increase over the hotspot – this is the simplest possibility, involving a simple increase of the capacity over the hotspot. In some cases, this type of action is possible as (sometimes) the actual traffic is often higher than the declared capacities. The choice of a particular hotspot over which to apply the capacity increase will be guided by the historical data analysis presented in section 4.5, in particular looking into the daily entry counts statistics into the sector in question. Several iterations will probably be needed in order to come up with the exact mitigation scenario. The location of hotspots depends on the modelling results. Then, it is foreseen to start with one or two most saturated hotspots and see how the ESFP results change – it is not a given that the increase of the capacity over one hotspot would not create other hotspots. It is also possible that by changing capacity of a small number of hotspots, we can almost resolve the hotspots over the network. As each hotspot involves a significant number of flights that are interconnected, it is not possible to predict the exact impacts of the foreseen capacity mitigation actions, which pushes towards the iterative approach.

2. Change of the sector configuration, switching to one of higher capacity over the hotspot. The historical data contain the list of possible configurations and the declared capacities of each of the active sectors. Thus the choice of the configuration will depend on the location (and duration) of the hotspot and the analysis of the capacity of past configurations in that area of airspace.

In case the time (and needed effort on the model adjustments) allows, the consortium would also like to try a different approach to the capacity mitigation, as was suggested by the ADAPT Advisory Board in May 2018. In this approach, the ADAPT models would be run on the highest capacity configurations and slowly closing (or keeping them open) the sectors when and where the demand is lower.

5.2.2 Pricing scheme mitigation

European Air Navigation Service Providers (ANSP) finance their operations by charging airspace users according to EC Regulation 391/2013 (see European Commission, 2013). Air navigation service (ANS) charges are composed of en route and terminal charges, for the provision of air navigation services for the en route and terminal segments of the flight, respectively. En route charges, to be paid by a flight, are currently calculated as the sum of the charges generated in each individual State traversed by this flight. Such national charge is equal to the product of the distance factor[5], the weight factor of the aircraft used[6], and a national unit rate (the rate is set annually by each State). Article 16 of EC Regulation 391/2013 states that “Member States [...] may [...] reduce the overall costs of air navigation services and increase their efficiency, in particular by modulating charges according to the level of congestion of the network in a specific area or on a specific route at specific times. [...] The modulation of charges shall not result in any overall change in revenue for the air navigation service provider [...]”. This feature of Regulation 391/2013 provides Member States and ANSPs with an instrument to implement demand management for dealing with the recurring congestion problems.

Within this regulatory framework, we will *strive to design and implement one or both* airspace and trajectory-based pricing schemes. The former approach is a peak-load pricing mechanism that has been extensively studied in the WP-E SATURN project and has shown that en route charge modulation could, indeed, represent a viable measure to redistribute traffic when congestion is expected (Bolić, Castelli, & Rigonat, 2017). The hotspots identified by the ESFP model are the natural candidates for setting a higher unit rate in order to deviate the traffic from them and then alleviate the congestion.

Trajectory pricing would introduce some significant changes vis-à-vis the current pricing policy. In fact, there is a degree of freedom in the path-toll system (vs. the link-based one), which can be exploited by introducing some additional criteria, such as,

- airspace users willing to have “premium service” routes would be asked to pay more, if these routes are of major importance for them (COCTA consortium, 2018). Likewise, the use of off-

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[5] The distance factor is equal to the hundredth of the great circle distance, expressed in kilometres, between the aerodrome of departure within, or the point of entry into, the airspace of the flight information regions of the state and the aerodrome of first destination within, or the point of exit from, that airspace. The entry and exit points are the points at which the lateral limits of the airspace are crossed by the route described in the last filed flight plan. The actual distance considered is equal to the distance calculated on the basis described above less 20 km for each take-off and each landing in a given state.

[6] The weight factor is the square root of the quotient obtained by dividing by 50 the number of metric tons in the maximum take-off weight of the aircraft.

load routes could be incentivised by reducing their charging costs and therefore reducing the pressure on some hotspots, which in turn may allow to enlarge the TWs associated with the flights traversing them.

- airspace users willing to have "flexibility" in terms of TW size: the greater the flexibility requested, the greater the price. Such price differentiation could foster an improved management of operations within an airline: for instance, the greater flexibility given to a flight is achieved at the expense of reduced flexibility for flights of the same airline. In addition, this mechanism could implement a sort of "risky service", i.e., by accepting strict time windows in exchange of low charges, an airline implicitly accepts that its flights are the first to be rerouted or delayed in case such time windows cannot be met.

All charging mechanisms should guarantee that ANSPs are able to recover their operating costs (revenue neutrality property) and that AUs are able to perform flights (no flight cancellation is allowed).

5.3 Tactical assessment scenarios

The tactical impacts assessment (i.e. validation) scenarios focus on the type of disturbances to introduce in the system in order to make the tactical assessment more realistic, and to be able to draw robust conclusions.

5.3.1 Flight centric view scenarios

The WP4 assesses the ADAPT models from the aircraft performance point of view: evaluating the expected fuel consumption and arrival delays as a result of employing TWs. The assessment will take into account the following scenarios:

1. Inclusion of the wind forecast ensembles from EWCMF (see section 2.3 for explanation of input data) into the TWs optimisation model at the tactical level. The TWs of the ADAPT models are updated with the information on the variation of sector crossing times due to wind uncertainty.
2. Evaluation of the impact of departure delays on the TWs. The departure delays will be determined based on the departures times available in M1 and M3 files from DDR2.
3. Evaluation of the impact of both weather (wind ensembles) and departure delay on the TWs.

5.3.2 Network-wide assessment scenarios

As the main aim of this task is to provide an assessment of the impact the ADAPT strategic solution would have on the tactical operations, from an operational point of view, four scenarios will be used:

1. Airline departure delay. In this scenario, the flights will "choose" their departure times from departure delay distributions. These distributions can either be created starting from the CODA departure delay data or by simply comparing the M1 and M3 DDR2 data.

2. Regulations. A set of regulations will be inserted into the simulation, thus making possible to assess how well the strategic planning performs in the presence of the tactical capacity reductions.
3. Weather events. A set of surrogate weather events will be inserted into the simulations, thus making possible to assess the robustness of the proposed strategic solution. Surrogate weather events will be primarily obtained starting from appropriate distributions of empirical weather data. However, we will evaluate considering reference distributions with Gaussian, exponential and power-law tails in order to assess the role of extreme events in determining the level of robustness of the proposed strategic solution.
4. Capacity stress-test. We will evaluate the possibility of performing simulations in which the number of aircraft present in a given airspace progressively increases, in order to mimic the foreseen increment of global air traffic. An alternative scenario would be the one where the total number of aircraft remains unchanged and the sector capacity constrains are randomly changing. Both scenarios will allow us to assess the robustness of the proposed strategic solution.

5.4 Indicators for assessment

The ESFP models assign flight plans strategically, by redistributing 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 capacity-demand imbalances are avoided, the resulting traffic pattern affects other, as important, factors. Therefore, a comprehensive assessment takes into account several indicators and looks into the resulting trade-offs.

The initial[7] list of indicators to be taken into account are:

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.
   a. Route charges per flight. This indicator measures the route charges imposed on flights.
   b. Fuel costs. Measures the fuel costs for the operated flight.
4. 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., one hour).
5. Distribution of TWs. This indicator shows how many flights are flexible (TW of max length) and the number of flights being assigned each of the durations that are lower than the maximum one. Important when comparing strategic scenarios.

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[7] In the course of the project it might be necessary to change the list by excluding some of the listed indicators and adding other, more pertinent ones.

6. Adherence to TWs. This indicator measures how much the flights in the tactical environment adhere to their assigned TW – if a flight is performed within the assigned TW, it adheres to it. It is possible to express this in different ways – percentage, distribution, etc.
7. Number of conflict resolutions. In the network-wide tactical assessment, it is possible to assess how many conflict resolutions are needed for each proposed scenario.
8. di-FORK – this metric has been extensively used to measure the deviations from the original flight plans at the level of single trajectory segments. By comparing such deviations with a null hypothesis taking into account the natural heterogeneity of the system, it is possible to identify portions of the airspace where deviations occur more frequently than expected or less frequently than expected.
9. Complexity metrics. These are metrics known in the literature (i.e. Gurtner, Bongiorno, Ducci, & Micciché, 2017) and used in order to measure (tactical) congestion in relation to several operational aspects of the air traffic management.
10. Percolation - we will consider a technique already used in (Li et al. 2015) to investigate congestion at the level of urban mobility. The technique will be adapted to the air traffic system, by considering a navigation point network and trajectory segment loadings, allowing to identify trajectory segments (network links) having critical traffic loading (link weight).

6 Next steps and look ahead

In terms of data, other than minor 2017 updates to existing data, most of the datasets have already been acquired by the consortium. The only exception is the CODA data on the causes of delays, and the oceanic and non-CRCO states unit rates, which are not critical and will be acquired soon via EUROCONTROL and individual ANSPs' websites. Regarding the preparation of data, the team already loaded most of the data in the database. IFPS data need some cleaning and cross-validation but are otherwise ready and uploaded. Access to the data for all the partners is now completely set-up, but some adjustments might be needed, for example regarding the configuration of the database.

Finally, the team will actively monitor the needs for data, should new ones arise. WP2 runs almost until the end of the project to make sure that there is no bottleneck due to data availability, that new data can be obtained and prepared, if required, and that the project results are properly stored and used.

Apart from setting up the database, the initial statistical analyses and data preparation has been completed. Further, the scenarios and indicators are also defined (at the detail sufficient in this phase). Thus, the material needed by the WP3, WP4 and WP5 in terms of data, data elaboration (also stored in the database, under adapt_environment), scenario and indicator definition is available, completing the foundations for the modelling activities.

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8 Acronyms

ACI EUROPE: Airport Council International Europe

AIRAC: Aeronautical Information Regulation and Control

ANSP: Air Navigation Service Provider

ATC: Air Traffic Control

ATFCM: Air Traffic Flow and Capacity Management

ATFM: Air Traffic Flow Management

ATM: Air traffic management

AU: Airspace user

BADA: Base of Aircraft Data

CODA: Central Office for Delay Analysis

CPU: Central Processing Unit

CRCO: Central Route Charges Office

DDR2: Demand Data Repository

E-AMAN: Extended Arrival Manager

ECAC: European Civil Aviation Conference

GPU: Graphical Processing Unit

IFPS: Integrated Initial Flight Plan Processing System

NDA: Non-Disclosure Agreement

NM: Network Manager

SSL: Secure Sockets Layer

UNITS: Short name of ADAPT coordinator: Università degli Studi di Trieste

UoW: Short name of ADAPT partner: University of Westminster

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