The interdependency between the environment and capacity KPIs of the performance and charging scheme of the Single European Sky

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EXECUTIVE SUMMARY

There are few studies that investigate the relationship between environment and capacity within air traffic management, despite consensus that such an interdependency exists and influences the decision-making process of stakeholders.

This report quantifies the interdependency between the environmental and capacity key performance areas and analyses the factors influencing this interdependency. It focuses on the current KPIs defined in Commission Implementing Regulation (EU) 2019/317 and does not address factors outside its scope, such as CO_2 emissions or fuel burn.

The analysis conducted in this study demonstrates that high ATFM delays from various contributing factors have a negative impact on horizontal flight efficiency (HFE), proving the existence of an interdependency between the environment and capacity KPIs of the performance and charging scheme. However, the level of impact on HFE is found to be related to both the cause of the delay and its location.

Statistical models were developed to investigate the influence of different delay variables on HFE. This exercise revealed that an increase of one minute of average en route ATFM delay per flight causes an increase of 0.14 percentage points to HFE. Furthermore, the models showed that the theoretical average Union-wide HFE is estimated to be approximately 2.6% (within the sample of years analysed). This indicates that factors other than delay, such as inefficient route networks, airspace restrictions, and airspace user preferences, contribute significantly to HFE.

The analysis also depicted how differing delay causes have a varying impact on HFE depending on the season. The below table summarises the impact that a minute of delay per flight for each delay reason has on HFE for both the summer and winter seasons:

	Non-ATC capacity	Events	Weather	ATC disruption	ATC staffing	ATC capacity	Non-ATC disruption
Summer HFE impact	1.23 pp	0.45 pp	0.14 pp	0.12 pp	Negligible	Negligible	Negligible
Winter HFE impact	2.9 pp	0.49 pp	0.34 pp	0.18 pp	0.28 pp	0.19 pp	Negligible

Results of the modelling highlighted how delay occurrences in different Member States influence overall HFE performance with delays in Germany, Italy, and the Netherlands having the most significant impact on Union-wide HFE. At a local level, HFE was found to be influenced to varying degrees by delays in other Member States. Those most impacted by delays in other Member States include Estonia, Lithuania, and Latvia, while the least impacted include Ireland, Portugal, and Cyprus.

More generally, local HFE for Member States was found to be sensitive to en route ATFM delays in a relatively small number of other States, namely Germany, France, Cyprus, and Poland. These delays significantly affect the HFE performance of other States.

While these results are unique in their kind, they represent a first step in assessing the complex subject. The PRB recognises the need for further research to deepen understanding of the interdependency between capacity and environment in air traffic management, notably by incorporating additional datasets to provide wider perspectives on environmental performance and extending this work to include the influence of the cost of service provision.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Context

1 In recent years, public and political scrutiny of the aviation sector has increased, intensifying the debate on the environmental impact of aviation. With the European Commission's Green Deal of 2019, which sets out the new growth strategy for the European Union (EU) and the "Fitfor55 Package" proposal, all sectors in the European economy are expected to take steps towards climate neutrality by 2050.[1]

2 For the transport sector, including the aviation industry, the strategy is developed in the EU's Smart and Sustainable Mobility Strategy (SSMS), which includes improving the efficiency of the air navigation services in Europe. The European Commission expects that Air Traffic Management (ATM) improvements could reduce air transport CO_2 emissions by up to 10%, in turn helping to address the non-CO_2 impacts of the sector caused by flight inefficiencies and airspace fragmentation.[2]

3 The performance and charging scheme of the Single European Sky (SES) defines four key performance areas; each with a target that Member States are required to reach based on their performance plans.

4 During the COVID-19 pandemic, air traffic decreased significantly. In the SES area, in 2020, IFR (instrument flight rules) movements were 42% less than the STATFOR base forecast for 2020.[3] As a result, ANSPs were able to handle traffic without incurring major delays. During this year of low traffic and low delay levels, environmental performance improved. However, some Member States have struggled to meet the local environmental targets as traffic subsequently increased.

5 This pattern of poorer performance with increasing traffic suggests an interdependency between traffic levels and environmental performance, which should be taken into account when defining the targets for the key performance areas (KPAs). Whilst the interdependency between these KPAs is accepted within the air traffic management community, the precise relationship is not fully understood and has not been quantified.

1.2 Objectives

6 The objective of this report is to quantify the interdependency between the environment and capacity key performance areas (KPAs) and to better understand the key factors that define the interdependency using the current key performance indicators (KPIs) as defined in Commission Implementing Regulation (EU) 2019/317 (hereafter the Regulation).[4]

7 This report will not address interdependencies between environmental factors outside the scope of the Regulation, such as balancing CO_2 against non-CO_2 emissions, fuel burn, contrails, or noise. The study also recognises that the interdependency between environment and capacity will influence decisions taken by airspace users and ANSPs. A key factor for airspace users is cost (including route charges, connectivity, cost of delay versus cost of additional fuel burn, weather, and ANSPs' staff costs), which does not form part of the study, except where necessary to understand and explain decisions taken by stakeholders.

8 A detailed analysis into the interdependency between the capacity and environment KPIs has not previously been undertaken. This report assesses and quantifies the interdependency. The PRB recognises that it is a first step in a highly complex subject and that future work will be required to deepen the understanding of the interdependency.

9 Any future studies should incorporate additional datasets to provide wider perspectives on environmental performance and to extend this work to include the interdependencies between environment, capacity, and cost-efficiency.

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[1] A European Green Deal, European Commission and European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions.
[2] Mobility Strategy (europa.eu).
[3] PRB Monitoring Report 2020 (October 2021).
[4] The KPIs of the Regulation are horizontal en route flight efficiency of the actual trajectory for the environment KPA, and en route ATFM delays for the capacity KPA.

1.3 Report structure

10 This report consists of the following sections:

- Section 1: Introduces the context and objectives (current section).
- Section 2: Provides a review of previous studies assessing this interdependency (literature review).
- Section 3: Presents the results of qualitative analysis to investigate the existence of an interdependency between the environment and capacity KPAs.
- Section 4: Summarises the outcome of the modelling to quantify the interdependency.
- Section5: Presents the conclusions of this report.

11 This report is accompanied by an Annex detailing:

- The literature review of previous work undertaken on such interdependencies.
- Assumptions and models used to investigate and demonstrate the interdependency between the KPAs.
- Flight trajectory case studies, which demonstrate the interdependency between the environment and capacity KPAs using specific local examples.

2 LITERATURE REVIEW

2.1 Sources consulted

12 There are few studies that investigate the relationship between environment and capacity, despite there being wide consensus that such an interdependency exists and influences the decision-making process of stakeholders. The materials identified and consulted for this study are:

- Manual on global performance of the air navigation system (ICAO);[5]
- ATM global environment efficiency goals for 2050 (CANSO);[6]
- Environmental assessment: European ATM network fuel inefficiency study (Eurocontrol);[7]
- Impact assessment of the enhanced NM/ANSPs Network Measures for Summer 2019 (Network Manager);[8]
- Interdependencies within ATM performance in the context of a dynamic environment (Workshop BLUE MED FAB, and FABEC);[9] and
- Climate change and the role of air traffic control (Workshop Baltic FAB, FABEC, GARS, Vilnius TU).[10]

13 An analysis of the literature review is included in the Annex.

2.2 Summary of findings of the literature review

14 Six studies were reviewed with differing scope and purposes. Their findings related to the interdependency can be summarised as follows:

- Some of the studies confirmed the interdependency between the capacity and environment KPAs.
- None of the studies directly quantified the impact of a lack of capacity on horizontal flight efficiency performance as measured by the performance and charging scheme to a granular level.

15 Some studies indirectly quantified factors relating to the interdependency:

- Eurocontrol's environmental assessment report estimated the fuel inefficiency (measured through excess fuel burn) of the ATM network between take-off and landing to be between 8.6% and 11.2%.
- CANSO estimated that interdependencies relate to half of the total inefficiencies in the system.
- The Network Manager (NM) calculated the effect of optimising traffic flows during the summer period in 2019 leading to an average delay reduction of 1.72 minutes/flight with approximately 1.1 million additional nautical miles flown.

16 The literature review also shows that regulation and policy should support the balancing and prioritisation of interdependent KPAs, supported by accurate operational forecasts to account for interdependencies.

17 The PRB has not identified any studies that have quantified the direct relationship between a lack of capacity and HFE nor any existing models which could be applied to the subject at hand.

[5] Manual on global performance of the air navigation system, ICAO (Doc 9883).
[6] ATM global environment efficiency goals for 2050, CANSO (2008).
[7] Environmental assessment: European ATM network fuel inefficiency study, Eurocontrol (2020).
[8] Update on the NM action plan following NMB performance task force: ENM/s2019 measures and updated impact assessment of the Eurocontrol/NM action plan, Network Manager (NMB/19/24/7).
[9] Interdependencies within ATM Performance in the Context of a Dynamic Environment, Research workshop (2020).
[10] Climate change and the role of air traffic control, Research Workshop (2021).

3 ANALYSIS OF THE INTERDEPENDENCY THROUGH INFLUENCING FACTORS

18 This section shows the existence of an interdependency between environment and capacity by analysing the historic relationship between HFE and ATFM delays by reason or influencing factor. The analysis is performed at Union-wide level, with some examples for individual Member States.[11]

19 The factors influencing performance that were assessed include those that tend to affect flight trajectories, notably delays relating to weather, ATC capacity and staffing issues and ATC industrial action.

20 The analysis is based on a sample of days between the start of 2018 and end of 2022. Each bubble on the following graphs represents a specific day, where delays occurring due to the relevant influencing factor (weather, ATC staffing and capacity, ATC strikes) represented over 50% of total en route ATFM delay on that given day.

21 All the graphs show that the year 2022 is an outlier in terms of Union-wide HFE performance relative to traffic levels. This is because of the closure of Ukrainian, Belarussian, and Russian airspace to European carriers. These events have led to a shift in traffic flows throughout the SES, resulting in inefficiencies measured by HFE.

3.1 Weather

22 Weather phenomena (including intensity and frequency) impact flight trajectories and capacity due to the potential rerouting around them.[12]

23 ATFM regulations relating to storms impact airspace capacity and flight efficiency. They lead to route restrictions and airspace users circumnavigating these areas. Due to the high density and high complexity of multiple areas, a major weather event located near a capacity-constrained sector may trigger rerouting for a significant number of flights and potentially result in knock-on performance impacts across the network. Horizontal flight efficiency can also be affected where airspace users plan routes to benefit from wind and jet streams (that are not necessarily the shortest routes) allowing faster, more fuel-efficient trajectories.

24 Figure 1 shows the relationship between weather-induced delays, HFE, and traffic levels (IFR movements), whereby higher traffic tends to be associated with poorer performance of HFE and delays in the years 2018 to 2022.[13] This is demonstrated in the figure with the larger bubbles (higher weather-related delay) in the top right of the data set (higher levels of flight inefficiency occurring with higher levels of both traffic and weather-related delay).[14] The phenomenon can be explained by re-routing being more pronounced when sectors lack capacity to accommodate the re-routed aircraft.

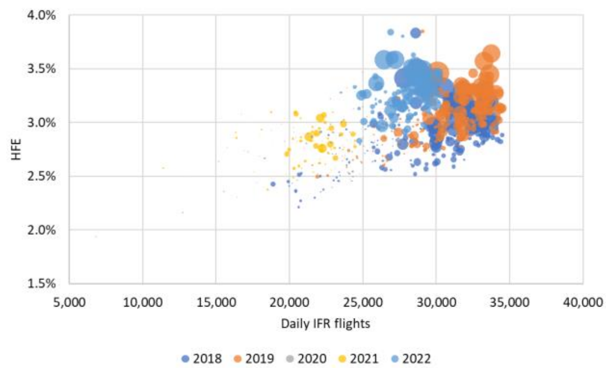

Figure 1 – Relationship between weather delays, traffic levels, and HFE at Union-wide level (Source: PRB elaboration). Bubble size indicates extent of weather-related delay in minutes, whereby the largest bubble represents 174,533 minutes).

3.2 ATC capacity and staffing

25 Both ATC capacity and ATC staffing are factors that ANSPs can influence. ATC capacity delays occur during periods of high traffic demand, when one or more ATC sectors in a Member State are projected to exceed capacity limits (unable to

[11] As the environment KPI (KEA) is defined as an annual average, with exclusion of the ten highest daily values and the ten lowest daily values from the calculation, daily and monthly values are referred to as Horizontal Flight Efficiency (HFE).
[12] The most important weather phenomena for aviation operations: Wind, turbulence, and precipitation (rain, snow). In general, turboprops are more sensitive to weather impacts than jets. If weather phenomena occur within 40NM from the origin/destination, their impact is not fully visible on KEA due to KEA calculation algorithm.
[13] Note: As horizontal lights efficiency is measured in (unnecessary) route extension, a higher HFE indicates poorer performance.
[14] The PRB Annual Monitoring Report 2022 will provide a more detailed description.

meet demand) leading the ANSP concerned to declare ATFM regulations to limit future traffic flow in the regulated sectors. ATC staffing delays are caused when (despite pre-tactical planning) there are fewer ATCOs on duty than required to open the planned number of ATC sectors. In both cases, airspace users wishing to operate in the impacted sectors must either wait on the ground for their designated slot or route around the constraint. Re-routing can impact HFE through an additional distance flown (Figure 2 and Figure 3).

26 These figures also show how the yearly number of flights in the SES influences performance. The years 2018 and 2019 (orange and blue in the figures) were more sensitive (in terms of delay and HFE variation) than 2021, as more flights were operating in those years within the SES airspace. With increasing number of flights, the number of optimised trajectories available to airspace users decreases as a result of maximum sector throughput being reached.

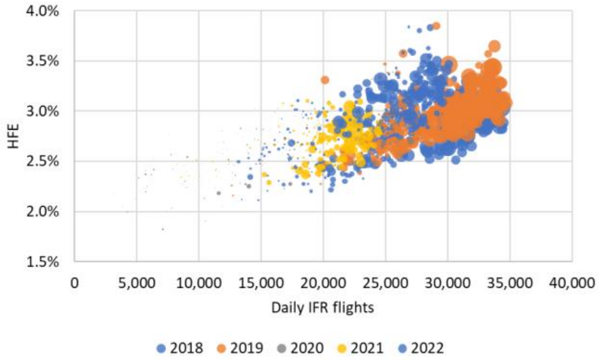

Figure 2 – Relationship between ATC staffing delays traffic levels and HFE at Union-wide level (Source: PRB elaboration). Bubble size indicates extent of ATC staffing-related delay in minutes, whereby the largest bubble represents 72,966 minutes.

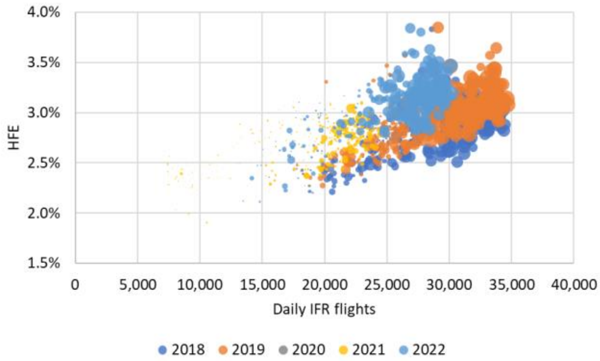

Figure 3 – Relationship between ATC capacity delays, traffic levels and HFE at Union-wide level (Source: PRB elaboration). Bubble size indicates extent of ATC capacity-related delay in minutes, whereby the largest bubble represents 87,202 minutes.

3.3 ATC strikes

27 ATC strikes can cause major disruptions across Europe, namely cancellations, delays, and deviations from the ideal trajectory, because:

- The airspace is closed, leading airspace users to avoid the airspace; or
- The airspace is open at reduced capacity leading to both increased delays and rerouting around the affected area; or
- The Network Manager reroutes the flows to mitigate the delays.

28 Airspace users tend to avoid airspace (either voluntarily or under Network Manager rerouting) where strikes take place, resulting in deviations from ideal entry and exit points to individual airspace, and higher (inefficient) HFE. Although the limited number of ATC strikes per year, they have the potential to cause a major deterioration of HFE and capacity on the days of strikes. At Union-wide level, ATC strikes can cause delays up to eight minutes per flight and HFE up to 4% measured across all flights on the given strike day (Figure 4, next page).

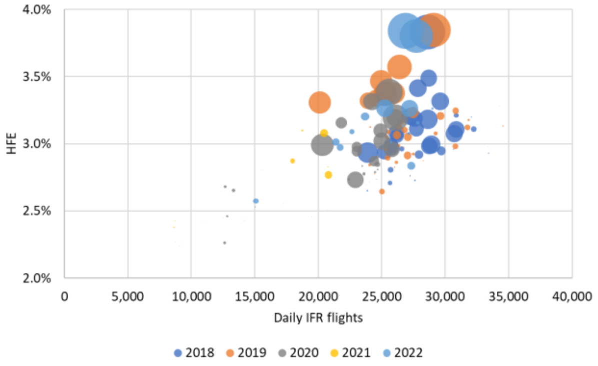

Figure 4 – Relationship between ATC strikes, traffic levels and HFE at Union-wide level (Source: PRB elaboration). Bubble size indicates extent of ATC strike-related delay in minutes, whereby the largest bubble represents 210,309 minutes.

3.4 Key findings

29 The above analysis demonstrates that high levels of ATFM delays from various contributing factors have a negative impact on HFE.

30 For some of these contributing factors (weather, ATC capacity, ATC staffing delay causes), higher traffic at Union-wide level leads to further delays and inefficiency. This shows that an interdependency exists between the environment and capacity KPIs of the performance and charging scheme. The following section seeks to quantify this interdependency.

4 QUANTIFICATION OF THE INTERDEPENDENCY THROUGH STATISTICAL ANALYSIS

31 The interdependency between ATFM delay and HFE has been analysed using statistical models to understand the influence of different variables on HFE. All the models examined the relationship between HFE and average en route ATFM delays per flight. The models analysed daily data between 2017 and 2021.[15]

32 The focus of the analyses is on Union-wide daily HFE: The different models examine how these varied, and if/how en route ATFM delays (and their different components) explained these variations.

33 Based on the outcome of Section 3, three research objectives were formulated and tested:

- To quantify the interdependency between Union-wide HFE and en route ATFM delays;
- To quantify if/how en route ATFM delays due to different causes have different impacts on HFE and how seasonal changes affect the interdependency; and
- To estimate if/how en route ATFM delays occurring at different locations of the European ATM network have different impacts on Union-wide HFE.

34 The results of the statistical analyses are summarised in the following sub-sections.[16] The detailed technical description of the models is included in the Annex. The Annex also illustrates the output of the following analyses through case studies of selected flight trajectories.

4.1 *Interdependency between HFE and ATFM delays*

35 The results show that the interdependency between Union-wide HFE and en route ATFM delays exists and can be quantified. As delays increase, HFE deteriorates: An increase of one minute of average en route ATFM delay per flight causes an increase of 0.14 percentage points to HFE. Moreover, the results show that, theoretically, on days when there are no en route ATFM delays, Union-wide HFE is estimated to be on average 2.59%. In comparison, the average yearly HFE over the period calculated from the actual data was 2.71%.

4.2 *The relationship between HFE and specific delay causes*

36 En route ATFM delays are generated by ATFM regulations, which limit how many aircraft can fly through a given block of airspace in a defined period of time. The reasons behind the ATFM regulation may determine how long the delays occur, what volume of the airspace is affected and to what extent airspace capacity is reduced. It is assumed that these reasons for ATFM regulations affect the relationship between delays and flight efficiency to differing extents. In order to explore these differences, the analysis considered en route ATFM delays per delay cause group (namely ATC capacity, ATC staffing, ATC disruptions, weather, special events, non-ATC capacity, and non-ATC disruptions).

37 Furthermore, air traffic in the SES area has seasonal trends: Traffic levels, major flows, and traffic complexity are all significantly different during the peak summer period and during winter.

38 To understand and quantify the relationship between HFE and en route ATFM delays per cause, the analyses aim to explain variations in the daily Union-wide HFE with daily average en route ATFM delays per flight for each delay reason group.[17]

39 Using delay reason groups instead of individual delay codes simplifies the analysis, but still identifies delays largely within the control of ANSPs (ATC capacity, ATC staffing, and ATC disruptions). Delay groups represent delays similar in their operational characteristics.

40 The delay reason groups are from the datasets published by the Aviation Intelligence Unit of Eurocontrol and are shown in Table 1 (next page).[18]

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[15] The data used in the analysis was sourced from the datasets provided by the Aviation Intelligence Unit of Eurocontrol, and the calculation of the different metrics was also performed applying the methodology of Eurocontrol.

[16] The domain of applicability of the results is limited to the geographical scope and time period of the analysis. While the findings are statistically significant and robust, careful consideration is required before generalising the results.

[17] While there is no specific delay code for delays related to military operations, these delays are captured in the figures under delay codes “M”, “O”, and “P”, depending on the nature, scale, and duration of the military operation in question.

[18] https://ansperformance.eu/definition/atfm-delay-codes/.

Disruption	Code	Description
ATC Capacity	C	Indicates that the capacity provided by the ANSP is generally lower than the demand.
ATC Staffing	S	Indicates that the ANSP cannot provide sufficient capacity due to staffing issues (e.g. controllers being on sick leave, shortage of working hours, etc.).
ATC Disruptions	I & T	Indicates that the ANSP cannot provide sufficient capacity due to industrial action or failure of technical equipment.
Weather	W & D	Indicates that the capacity of the ANSP is reduced due to adverse weather in general or due to de-icing.
Events	P	Indicates that delays are occurring due to large-scale special events (e.g.: major sports events, system transitions, large-scale military exercises, etc.).
Non-ATC Capacity	G, M, R & V	Indicates that delays are occurring due to reduced/insufficient aerodrome capacity, airspace management reasons, routing, or environmental issues.
Non-ATC Disruption	A, E, N, O & NA	Indicates that delays are occurring due to accidents/incidents, non-ATC equipment failure, non-ATC industrial action, other delay reasons or delays without specific reasons.[19]

Table 1 – Delay reason groups (Source: Aviation Intelligence Unit, Eurocontrol).

41 Performance monitoring of previous years indicates that seasonality influences en route ATFM delays. Based on this finding, the analysis examines if the relationship between flight efficiency and delays is also subject to seasonality.[20] Summer and winter seasons are defined on the basis of general traffic patterns of the past years. The summer period lasts from May to September, and the winter period from October to April.

42 The results of the analysis show that delays due to ATC capacity have a negligible impact on Union-wide HFE in the winter.[21] In the summer, a minute of delay per flight in this group adds 0.2 percentage points to HFE. This seasonality can be explained by the higher traffic levels which occur during the summer, meaning capacity is under more strain and such delays are more persistent, hence making rerouting a preferable option (rather than waiting on the ground) for airspace users.

43 ATC staffing delays do not have a significant impact on Union-wide HFE in the summer period. In the winter, a minute of ATC staffing delay per flight adds 0.28 percentage points to HFE. This may be explained by the seasonal trends in sick leave (being more common, for example for influenza, in the winter months).[22]

44 The impact of ATC disruption related delays had a similar level of impact on HFE in both summer and winter (each minute of average delay per flight adding 0.12 percentage points to HFE in the summer and 0.18 percentage points in the winter). This is because there is no clear seasonal tendency for the occurrence of such delays, which tend to be relatively localised (equipment failures) and/or planned (industrial action).

45 Weather-related delays have a stronger impact on Union-wide HFE during the winter, with each minute of average delay per flight adding 0.34 percentage points to HFE. However, there is also an (lesser) impact in the summer, when with each minute of average delay per flight added 0.14 percentage points to HFE. This can be explained by the differing types of weather events occurring in summer and winter. In summer, these tend to be related to convective conditions and storms which require airspace users to route around the affected area.

46 Event-induced delays have the second most important impact on HFE, with almost equal effects

[19] A detailed definition of the codes used to denote ATFM regulations can be found in the Network Manager ATFCM Operations Manual.
[20] https://wikis.ec.europa.eu/display/eusinglesky/Public+Library.
[21] Summer and winter in the following paragraphs refer to the periods defined in paragraph 41.
[22] https://flunewseurope.org/.

noted in both seasons (each minute of average delay per flight adding 0.45 percentage points to HFE in summer and 0.49 in winter). This lack of seasonality occurs because events are usually planned in advance, meaning routes and schedules can be adapted accordingly.

47 Delays due to non-ATC capacity issues have the highest impact on HFE, which may also be because this category is a collection of different reasons. This is most significant in the winter when each minute of average delay per flight adds 2.9 percentage points to HFE. The impact remains strong in the summer, although less so, with each minute of average delay per flight adding 1.23 percentage points to HFE.

48 On the other hand, ATC capacity has a higher impact in the summer, which can be explained by the increased traffic and congestion occurring during these months, straining network capacity and slot flexibility. As a result, airspace users will often prefer to take a longer (potentially less efficient) route.

49 Finally, delays relating to disruptions not related to ATC (non-ATC disruption) did not have a significant impact on Union-wide HFE in the summer or in the winter.

50 The reasons for the varying scales of delay impact on HFE can mostly be explained by the operational reactions of airspace users to different delays. When delays occur due to a larger-scale disruption such as issues with non-ATC capacity, events and weather phenomena, either a part of the affected airspace is blocked from traffic (or at least generally avoided by airspace users) or the airspace throughput is greatly reduced for longer periods of time. Thus, airspace users are more likely to reroute and fly less horizontally efficient trajectories. On the other hand, when delays are due to ATC capacity, airspace users typically do not reroute as long as the duration of the delay is not disrupting the schedule of their operations.

4.3 The impact of local capacity issues on Union-wide HFE

51 In addition to quantifying the relationship between HFE and different types of en route ATFM delays the analysis also assesses how delays occurring at different places in the network affect Union-wide HFE.

52 Traffic flows, capacities, and airspace structures are not uniform across the SES ATM network. As with almost all networks, constraints or disruptions introduced at different places may have different outcomes in terms of network performance. In order to better understand these network effects, the analysis considered the relationship between Union-wide HFE and en route ATFM delays per flight occurring in different Member States.

53 In terms of the impact on Union-wide HFE, average delays per flight in Germany, France, Poland, Spain (Canarias and Continental), Hungary, Slovakia, Cyprus, Italy, the Netherlands, and Estonia are the most significant in the analysis. Delays in Germany show the highest impact (one minute of average delay per flight increased Union-wide HFE by 0.11 percentage points).

54 Delay per flight occurring in Spain Canarias, Slovakia, and Estonia show an inverse relationship with HFE (one minute of average delay decreased HFE by 0.04, 0.09, and 0.14 percentage points respectively). The reason for this relationship between delays occurring in States at the border of the SES area and SES-wide HFE requires further investigation.

55 Figure 5 (next page) provides a geographical representation of the States where local delays have the most significant impact on Union-wide HFE.

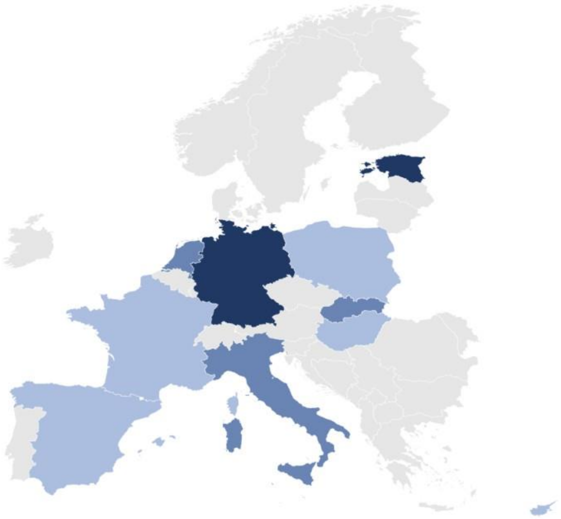

Figure 5 – Significant Member States in the Union-wide regression model (Source: PRB elaboration). Member States in darker shading have a stronger impact (higher coefficient) on Union-wide HFE.

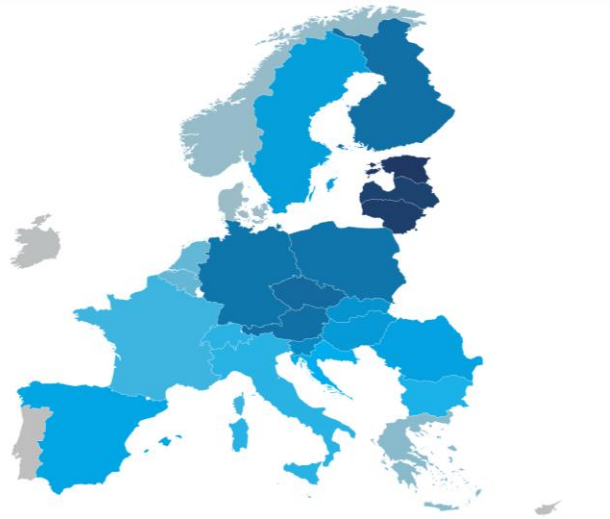

Figure 6 – The strength of the Member State-level regression models expressed by the R^2 value (Source: PRB elaboration). Member States in darker shading have a stronger relationship (higher R^2 value) between capacity underperformance and horizontal flight inefficiency.

4.4 Member State-level assessment

56 In order to understand the local specificities, the analysis examined the relationship between the HFE of each Member State and average en route ATFM delays per flight occurring in the network. The results showed significant differences in how strongly en route ATFM delays explained variation in HFE across Member States.

57 The analysis concludes that the relationship between the Member State HFE and en route ATFM delays in the network is strongest in Estonia, Lithuania, and Latvia, where 65-68% of HFE variation is explained by variations in the delays per flight in other Member States. In contrast, in Ireland, Portugal (Lisboa FIR) and Cyprus only 5-6% of HFE variation is explained by variations in en route ATFM delays per flight generated in other Member States.

58 For a group of Member States (Germany, Poland, Czech Republic, Austria located in Central Europe, and Finland), 51-55% of the variation in HFE is explained by variations in en route ATFM delays per flight. Figure 6 presents the strength of the relationship between HFE and ATFM delays.[23]

59 Delays in Cyprus, Germany, France, and Poland are found to significantly influence HFE in more than 20 Member States, whereas some other Member State-level delays were only significant for a single other Member State (e.g. Bulgaria, Latvia, Norway). This suggests a wider network effect of the interdependencies. Delays generated in a specific area may have a spill-over effect which has an impact well beyond neighbouring countries.

60 The varying level of delay impact on the HFE of other Member States can broadly be explained by traffic flows and the scales of delays faced. Germany and France accommodate the major traffic axes in the 'core' of the network while Cyprus and Poland accommodate traffic flows between western Europe and the far/Middle East. Airspace users avoiding delays in this airspace can have more significant upstream/downstream impacts on HFE in other Member States.

61 Similarly to the Union-wide analysis, delays in some Member States on the borders of the SES have an inverse relationship with the HFE of many Member States. When delays in Spain Canarias, Slovakia, and Estonia had a significant impact on the HFE of another Member State, this almost always had a beneficial impact on the HFE of other Member States. Figure 7 (next page) shows an overview of how frequently the delay occurring in

[23] This is demonstrated by the strength of the regression model.

Member States had significant impacts on the local HFE.

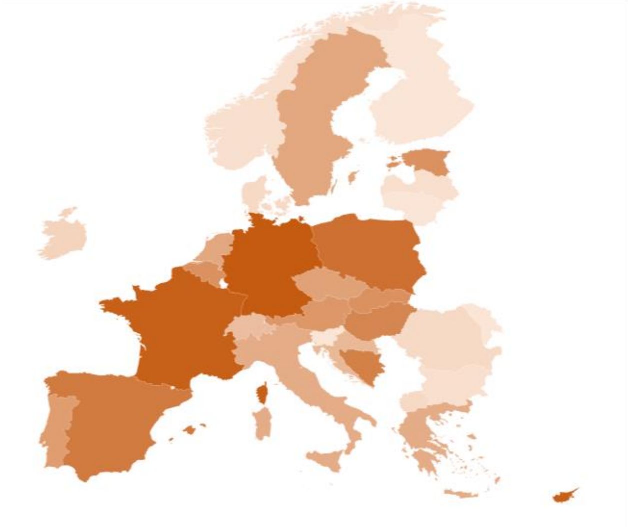

Figure 7 – Frequency of Member State-level en route ATFM delay having a significant impact in the Member State-level regression models (Source: PRB elaboration). A darker shading indicates that the en route ATFM delays of the Member State influenced HFE performance in other Member States.

5 CONCLUSIONS

62 The study shows that en route ATFM delay has a negative effect on horizontal flight efficiency. The impact varies according to a number of factors including the cause of delay, the location of the delay, the length of delay, and the season and where the HFE is measured.

63 **Conclusion 1:** Delay causes have a varying impact on HFE depending on the season due to the nature of the disruption they cause. Table 2 summarises the impact that a minute of delay per flight for each delay reason has on HFE:

Delay reason	Summer HFE impact	Winter HFE impact
Non-ATC capacity	1.23 pp	2.9 pp
Events	0.45 pp	0.49 pp
Weather	0.14 pp	0.34 pp
ATC disruption	0.12 pp	0.18 pp
ATC staffing	Negligible	0.28 pp
ATC capacity	Negligible	0.19 pp
Non-ATC disruption	Negligible	Negligible

Table 2 – Summary of the impact that a minute of delay per flight has on HFE by delay reason and season (Source: PRB elaboration).

64 **Conclusion 2:** Without any delays, the Union-wide HFE is estimated to be on average around 2.6% within the sample, suggesting that this amount of HFE is attributable to other factors than delay (e.g. inefficient route networks, airspace restrictions, airspace user route preferences).

65 **Conclusion 3:** Delays occurring in different Member States have a varied effect on Union-wide HFE, with delays in Germany, Italy, and the Netherlands having on average the larger (more detrimental) impact on Union-wide HFE.

66 **Conclusion 4:** HFE at a local level is influenced, to varying degrees, by en route ATFM delays in other Member States. Those with HFE impacted heavily by delays in other Member States include Estonia, Lithuania, and Latvia. Those whose HFE is not impacted very much include Ireland, Portugal (Lisboa FIR), and Cyprus.

67 **Conclusion 5:** The local HFE in the Member States of the SES area tend to be sensitive to en route ATFM delays in a relatively small number of other States (Germany, France, Cyprus, and Poland).

68 **Conclusion 6:** The impact of delays on HFE can be related to both the cause of the delay and the location. ATC strikes were also found to cause significant underperformance on specific days, with delays up to eight minutes per flight and HFE up to 4% measured across all flights on the given strike day.

The interdependency between the environment and capacity KPIs of the performance and charging scheme of the Single European Sky

Annex

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TABLE OF CONTENTS

1 INTRODUCTION

1 This Annex to the report on the interdependency between the environment and capacity key performance indicators within the performance and charging scheme provides supporting information relating to the study.

2 This Annex includes:

- Section 2: The detailed literature review, a summary of which was included in Section 2 of the main report.
- Section 3: A description of the methodology and summary of results of the statistical analysis.
- Section 4: Flight trajectory case studies to illustrate the interdependency between the environment and capacity on specific days and explore the conclusions of the statistical analysis.

2 LITERATURE REVIEW

3 This section presents the outcome of the literature review of previous work relating to the interdependency between the environment and capacity KPAs. The following sources were reviewed:

- Manual on global performance of the air navigation system (ICAO);
- ATM global environment efficiency goals for 2050 (CANSO);
- Environmental assessment: European ATM network fuel inefficiency study (Eurocontrol);
- Impact assessment of the enhanced NM/ANSPs Network Measures for Summer 2019 (Network Manager);
- Interdependencies within ATM performance in the context of a dynamic environment (Workshop BLUE MED FAB, and FABEC); and
- Climate change and the role of air traffic control (Workshop Baltic FAB, FABEC, GARS, Vilnius TU).

2.1 Manual on global performance of the air navigation system (ICAO Doc 9883)

4 This manual (Doc 9883) was produced by the ICAO Air Traffic Management Requirements and Performance Panel in 2009 and addresses the basic and common performance management terminology and techniques. The aim of the manual is not to analyse the interdependencies within the ATM system, but rather to give an overview of performance planning and management techniques. While the manual does not directly address the interdependency between environment and capacity areas, it recommends that there should be an approach to deal with the issue of performance trade-offs.

5 Appendix B, 4.3 of the manual is of particular relevance. It analyses the trade-offs between key performance areas, including the link between flight efficiency and capacity. It highlights the example of objectives related to providing flight trajectories closer to user preferred trajectories having to be balanced against the objective of increasing capacity.

6 The manual suggests that in order to improve performance when there are interdependencies, one must first determine if there are conflicting objectives that need to be balanced. When conflicting objectives emerge, the manual raises techniques from 'multi-criteria decision-making (MCDM)', such as the development of a common performance metric across multiple objectives or the technique of the analytical hierarchy process (AHP) allowing decision makers to rank preferences.

7 It is also highlighted that after the initial target setting and where simultaneous meeting of different targets is not possible, the balance between targets must be adjusted so that they reflect acceptable and feasible compromise.

8 In Chapter 2 (Measuring and Assessing performance), the manual highlights the necessity to develop an understanding of the interrelationships between different performance objectives within a KPA and between different KPAs.

9 These interdependencies can allow improvement in performance in one KPA via a trade-off in performance within another KPA. The manual gives examples of the interdependencies including between the environment and capacity KPA. For example, Continuous Descent Operations (CDO) procedures may provide improvements in both noise and emissions at the expense of capacity.

2.2 ATM global environment efficiency goals for 2050 (CANSO)

10 In its report of 2012, ATM global environment efficiency goals for 2050, CANSO presented its aspirational goals for fuel efficiency improvements and addressed the topic of interdependencies (such as capacity limitations, weather, noise, and others) and how they may affect fuel efficiency.

11 These efficiencies may be achieved by introducing a range of initiatives. Some of these can be introduced by ANSPs directly, such as new operational procedures. However, many rely on other stakeholders of the ecosystem, such as airspace users, airports, and regulators to bring change. Improvements are also possible by reducing the effect of interdependencies such as increasing capacity and reducing noise restrictions.

12 The report, now over ten years old, estimated that interdependencies relate to half the total inefficiencies in the system at that time, however, it does not go into the details of the environment and capacity KPA interdependency.

2.3 Environmental assessment: European ATM network fuel inefficiency study (Eurocontrol)

13 In a 2020 study, Eurocontrol estimated the fuel inefficiency of the ATM network in 2019 to be between 8.6% and 11.2% from take-off to landing for flights within Europe.

14 When addressing operational efficiency, the report states that it is a result of various interactions between airspace users, airport operators, and ATM. As such, the report highlights that operational efficiencies cannot be reduced to zero (for example due to safety requirements, and operational trade-offs) and that improvements require joint efforts from all stakeholders.

15 The report does not directly address the interdependencies, however, particularly on HFE, the analysis undertaken suggests that the lack of capacity and the resulting ATFM constraints have a significant negative effect on flight efficiency. Where traffic density is highest and FRA is not fully implemented, the en route flight efficiency is comparatively low. Where FRA is fully implemented, there is a clear 0.5% higher flight efficiency versus other states.

16 In addition, the Think Paper #10 (April 2021) published by Eurocontrol, identifies solutions that exist and could contribute to making every flight as environmentally efficient as possible including on-board systems, minimisation of the adoption of hard ATM constraints such as permanent RAD restrictions by ATC and efficient/optimal capacity management of the Network (e.g. 4D business trajectories and Free Route Airspace).[1]

2.4 Impact assessment of the enhanced NM/ANSPs network measures for summer 2019 (Network Manager)

17 Due to the lack of capacity in some critical areas of the network and the complexity in managing the increasing traffic demand effectively and most efficiently at individual centre level during summer 2019, the Network Manager and all the involved ANSPs (eNM/S19) built a common strategy to prepare, manage and deliver a better service, focused on optimising the en route flows in between the centres and increasing the overall capacity and throughput.

18 An impact assessment of the measures proposed in the above-mentioned strategy was held from a flight efficiency, delay, user charges, and flight cancellations point of view. More precisely, it identified that the delay mitigation measures within the eNM/ANSPs/S2019 for the period 25th April 2019 to 6th November 2019 would result in:

- A delay reduction of 1.72 minutes/flight;
- Additional route extension for hundreds of flights leading to approximately 1.1 million NM flown extra, i.e., the equivalent of 6,600 tons of fuel, or increased emissions of 22,000 tons of CO_2; and
- Approximately 26,080 tons of additional fuel consumption from flight level constraints resulting in vertical flight inefficiency.

19 Although the report did not look at the environment and capacity performance areas interdependency per se, it still provided some facts confirming that changes regarding capacity in the network affects both horizontal and vertical flight efficiency.

2.5 Interdependencies within ATM performance in the context of a dynamic environment (Workshop BLUE MED FAB, FABEC)

20 The objective of the workshop (October 2020 - BLUE MED FAB and FABEC) was to investigate the impact of interdependencies within the ATM Performance areas of safety, environment, capacity, and cost-efficiency. One of the main conclusions of the workshop, was that interdependencies within the ATM performance areas exist and influence decision making.

21 The workshop found that the majority of the information available relates to the cost-efficiency - capacity trade-off, whilst there is a substantial lack of knowledge on metrics, methodology and, thus, trade-offs between the other areas. It concluded that interdependencies must be addressed appropriately in order to ensure robust operations, especially with the ongoing challenge of extreme traffic demand volatility and route preferences, forcing more flexible and adaptive ways of working.

[1] https://www.eurocontrol.int/publication/eurocontrol-think-paper-10-flying-perfect-green-flight.

2.6 Climate change and the role of ATC (Workshop Baltic FAB, FABEC, GARS, Vilnius TU)

22 The workshop (September 2021 - Baltic FAB, FABEC, GARS and Vilnius Gediminas Technical University) looked at the climate change and aviation nexus and considered the role of air navigation services as an essential enabling infrastructure. According to the main outcomes of the workshop there is a clear link between capacity, defined as a maximum number of flights passing through a sector, and the environmental impact.

23 The workshop concluded that clear policy priorities, enriched forecasts and improved efficiency benchmarks are required while the adaptation of the current performance and charging scheme should be considered to balance the KPAs of safety, environment, capacity, and cost-efficiency.

3 STATISTICAL ANALYSIS

24 This section provides the description of the methodology followed for the statistical analysis conducted by the PRB. The interpretation of the analysis is presented in the main report.

25 The study defined the following four key research objectives which have been modelled using linear regression (since there were no indications of non-linearity):

- Quantify the interdependency between Union-wide HFE and en route ATFM delays;
- Quantify how seasonal changes affect the interdependency between HFE and en route ATFM delays;
- Quantify if/how en route ATFM delays due to different causes have different impacts on HFE;
- Estimate if/how en route ATFM delays occurring at different locations of the European ATM network have different impacts on Union-wide HFE.

A total of three sets of models were used and are presented in the following sections.

3.1 Scope and data

26 The time period analysed covers the years from 2017 to 2021. The period selected is a balance between analysing a large enough sample while including the years most relevant for current-day operations. All days within this time period were considered during the analysis. The years prior to 2017 were not considered due to three main reasons:

- A significant traffic increase materialised during 2017-2019 (the number of IFR movements increased by 8.7% between 2019 and 2016 on average), which significantly altered the traffic flows and the distribution of traffic;
- Following the very high delays in 2018, the Network Manager started an intensive collaboration with ANSPs to develop and implement measures to avoid peak period delays; and
- Many ANSPs changed the ways they operated by introducing free route airspace, more arrival/departure managers and other advanced functionalities.

27 On the other hand, 2020 was kept in the scope, to ensure a continuous sample, despite its outlier nature due to the COVID-19 pandemic impact. The observations are at day level for each of the years considered (in total 1,826 observations).

28 Depending on the model, the observations are at Union-wide level (variable defined as '*_uw*'), or at FIR level (variable defined as '*_fir*'). When considering the FIR level observations, Spain was included in the datasets as Spain Continental and Spain Canarias. For the FIR level analysis, the States included are the ones within the scope of the performance and charging scheme (Member States) as well as States that are not part of the performance scheme but that are located along some of the major traffic axes in Europe.[2]

29 The source of the data is the Aviation Intelligence Unit of Eurocontrol. Data does not include post-ops adjustments.

30 All models have been tested for linearity, homoscedasticity, independency, and multicollinearity.[3] The variables have been adjusted during the analysis to fulfil the statistical assumptions.[4]

3.2 Interdependency between HFE and ATFM delays

31 The model generated to study the interdependency between HFE and the en route delays is:

Model_1: $$HFE\_uw_i = \alpha + \beta_1 DLY\_uw_i + \beta_2 S\_DLY\_uw_i + \varepsilon_i$$

Where:

- HFE_uw_i is the Union-wide average horizontal flight efficiency in day i;
- DLY_uw_i is the Union-wide average minutes of en route ATFM delay per flight in day i; and
- $S\_DLY\_uw_i$ is the Union-wide average minutes of en route ATFM delay per flight in

[2] U.K., Bosnia and Herzegovina, Serbia and Montenegro.
[3] Estimations have been performed with the JASP statistical tool kit. https://jasp-stats.org/.
[4] For the FIR level models, some of the observations of Finland, Lithuania, and Moldova have been removed due to multicollinearity.

day i multiplied by a seasonal dummy identifying the summer days (days between May and September).

32 The results of Model_1 are shown in Table 1. The regression is significant with an acceptable level of adjusted R^2.

Model_1		
Variable	Coefficient (Std. error)	t-value[5]
Intercept	2.59 (0.007)	339.826 ***
DLY_uw	0.14 (0.010)	14.315 ***
S_DLY_uw	-0.01 (0.010)	-0.983
adjusted R^2: 0.31		

Table 1 – Results of Model_1 (Source: PRB elaboration).

33 The daily average Union-wide en route ATFM delay (DLY_uw) is significant and positive. The coefficient shows that an increase of one minute of Union-wide average of en route delay per flight causes an increase by 0.14 percentage points in the Union-wide horizontal flight efficiency when considering all days in the year. Thus, an increase in the delay levels is negatively impacting the environmental performance. The delay variable multiplied by the seasonal dummy (S_DLY_uw) is not significant, showing that, on average, there is not a statistical difference in the impact of delays depending on the season.

34 Since the model includes a single explanatory variable, the intercept value may be interpreted as the value of the Union-wide daily HFE on days when there were no delays. Therefore, assuming no delays, the average day Union-wide HFE is estimated to be 2.59%.

3.3 Impact of different ATFM delay causes on HFE

35 The model generated to study the impact of different ATFM delay causes on HFE is:

Model_2:

$$HFE\_uw_i = \alpha + \sum_{n=1}^{7} \beta_n \, REAS\_uw_{n,i} + \sum_{n=1}^{7} \beta_n \, S\_REAS\_uw_{n,i} + \varepsilon_i$$

Where:

- HFE_uw_i is the Union-wide average horizontal flight efficiency in day i;
- $REAS\_uw_{n,i}$ are the Union-wide daily average en route ATFM delays per flight in day i for reason n. The reasons analysed are: ATC capacity (CAPATC), ATC staffing (STAFFATC), ATC disruptions (DSRPTNATC), weather (WEATHER), special events (EVENTS), non-ATC capacity (CAP), and non-ATC disruptions (DSRPTN); and
- $S\_REAS\_uw_{n,i}$ are the Union-wide daily average en route ATFM delays per flight in day i for reason n multiplied by a seasonal dummy identifying the summer days (days between May and September).

36 The results of Model_2 are shown Table 2. The regression is significant with an acceptable level of adjusted R^2.

Model_2		
Variable	Coefficient (Std. error)	t-value[6]
Intercept	2.58 (0.008)	329.39 ***
CAPATC_uw	-0.08 (0.039)	-2.103 **
STAFFATC_uw	0.28 (0.058)	4.880 ***
DSRPTNATC_uw	0.18 (0.015)	12.125 ***
WEATHER_uw	0.34 (0.108)	3.113 ***
EVENTS_uw	0.49 (0.160)	3.047 ***
CAP_uw	2.90 (0.312)	9.290 ***
DSRPTN_uw	-0.06 (0.028)	-2.136 **
S_CAPATC_uw	0.28 (0.046)	6.158 ***
S_STAFFATC_uw	-0.32 (0.069)	-4.666 ***
S_DSRPT-NATC_uw	-0.06 (0.038)	-1.694 *
S_WEATHER_uw	-0.20 (0.109)	-1.860 *
S_EVENTS_uw	-0.04 (0.220)	-0.199
S_CAP_uw	-1.67 (0.344)	-4.837 ***
S_DSRPTN_uw	-0.02 (0.139)	-0.154
adjusted R^2: 0.39		

Table 2 – Results of Model_2 (Source: PRB elaboration).

37 The results show that the delay reasons have a different impact on the HFE, with some of them being not significant at all. Moreover, differently from Model_1, the estimated coefficients show that for some of the delay reasons, the season can be a determinant on the impact on HFE:

- ATC capacity (CAPATC): The impact during winter is negligible and close to zero (-0.08),

[5] The number of asterisks indicates the singnificance level: * p < 0.1, ** p < 0.05, *** p < 0.001.
[6] The number of asterisks indicates the singnificance level: * p < 0.1, ** p < 0.05, *** p < 0.001.

while during summer is estimated to be 0.19 (i.e. -0.08+0.28);

- ATC staffing (STAFFATC): The impact during winter is positive and significant (0.28), while during summer becomes negligible and close to zero (i.e. 0.28-0.32=-0.04);
- ATC disruptions (DSRPTNATC): The impact during winter is positive and significant (0.18), and remains similar during summer (i.e. 0.18-0.06=0.12);
- Weather (WEATHER): The impact during winter is positive, significant, and relatively high (0.34), it remains positive and significant during summer but with a milder impact (i.e. 0.34-0.20=0.14);
- Special events (EVENTS): The impact is equal during both summer and winter, being positive, significant and relatively high (0.45 and 0.49);
- Non-ATC capacity (CAP): The impact is by far the highest among the delay causes. During winter it is estimated to be equal to 2.9, while decreasing in summer to 1.23 (i.e. 2.9-1.67=1.23); and
- Non-ATC disruptions (DSRPTN): The impact is negligible and close to zero for both winter and summer (-0.06, -0.08).

3.4 En route ATFM delays occurring at different locations of the European ATM network have different impacts on Union-wide HFE

38 To study if the interdependency between HFE and the en route delays are dependent on the location, two sets of models have been generated:

Model_3a: $$HFE\_uw_i = \alpha + \sum_{t=1}^{30} \beta_n \, DLY\_fir_{t,i} + \varepsilon_i$$

Model_3b: $$HFE\_fir_i = \alpha + \sum_{t=1}^{30} \beta_n \, DLY\_fir_{t,i} + \varepsilon_i$$

Where:

- HFE_uw_i is the Union-wide average horizontal flight efficiency in day i;
- HFE_fir_i is the average horizontal flight efficiency in day i for a specific FIR area; and
- $DLY\_fir_{t,i}$ is the average minutes of en route ATFM delay per flight in day i in a specific IFR area t.

39 Model_3a has been estimated through a stepwise variable selection method. Starting with the a model only including the intercept, the estimation introduces the next most significant explanatory variable (based on the "p" values), through a series of iterations, to maximise the R^2-value. Therefore, some of the original explanatory variables are omitted from the model because of their low explanatory power.

40 The results of Model_3a are shown in Table 3. The regression is significant with a relatively high level of adjusted R^2.

Model_3a		
Variable	Coefficient (Std. error)	t-value[7]
Intercept	2.57 (0.008)	336.071 ***
$DLY_{Germany}$	0.11 (0.006)	0.419 ***
DLY_{France}	0.02 (0.003)	7.144 ***
DLY_{Poland}	0.03 (0.006)	6.111 ***
$DLY_{Spain\ can}$	-0.04 (0.007)	-5.280 ***
$DLY_{Spain\ con}$	0.03 (0.010)	2.979 ***
$DLY_{Hungary}$	0.05 (0.007)	6.729 ***
$DLY_{Slovakia}$	-0.09 (0.028)	-3.357 ***
DLY_{Cyprus}	0.02 (0.005)	3.637 ***
DLY_{Italy}	0.08 (0.025)	3.183 ***
$DLY_{Netherlands}$	0.09 (0.028)	3.245 ***
$DLY_{Estonia}$	-0.14 (0.062)	-2.198 **
adjusted R^2: 0.49		

Table 3 – Results of Model_3 (Source: PRB elaboration).

41 The results show that the delay variables from the FIRs of Germany, France, Poland, Spain Canarias and Continental, Hungary, Slovakia, Cyprus, Italy, the Netherlands, and Estonia are retained in the model being significant for the impact on HFE.

42 Most of the Member States show a positive impact (i.e. an increase in delay per flight in the FIR, decreases the Union-wide environmental performance). However, Spain Canarias, Slovakia, and Estonia show a negative coefficient.

43 All the FIRs areas not included in the model are estimated to have a negligible impact on environ-

[7] The number of asterisks indicates the singnificance level: * p < 0.1, ** p < 0.05, *** p < 0.001.

mental performance. The results show that the locations of the delay are a determinant of the level of impact on the Union-wide HFE results.

44 Model_3b is a set of regressions, each of them with the dependent variable (HFE_fir_i) representing a specific FIR area (i.e. there is an estimation for each FIR area).

45 Due to the large number of regressions, results are shown in the following pages (Table 4). The interpretation of the results is similar to the ones of Model_3a with the only difference that the impact is at IFR level and not Union-wide.

Model_3b

Austria, adjusted R^2: 0.526		
Variable	Coefficient (Std. Error)	t value
Intercept	1.847 (0.009)	205.78***
DLY Germany	0.134 (0.007)	18.22***
DLY Austria	0.111 (0.01)	10.867***
DLY Croatia	0.056 (0.015)	3.681***
DLY Switzerland	0.068 (0.019)	3.634***
DLY Bosnia and Herzegovina	-0.103 (0.034)	-3.056**
DLY Latvia	0.309 (0.086)	3.578***
DLY Italy	0.122 (0.032)	3.799***
DLY Portugal (Lisboa FIR)	0.046 (0.014)	3.24**
DLY Serbia and Montenegro	-0.038 (0.012)	-3.061**
DLY Hungary	0.028 (0.011)	2.579**
DLY Spain (Canarias)	-0.015 (0.007)	-2.045**
DLY Poland	-0.013 (0.007)	-2.021**

Belgium, adjusted R^2: 0.193		
Variable	Coefficient (Std. Error)	t value
Intercept	3.437 (0.019)	184.146***
DLY Germany	0.138 (0.017)	8.177***
DLY France	0.051 (0.008)	6.381***
DLY Netherlands	0.309 (0.068)	4.536***
DLY Spain (Canarias)	-0.072 (0.015)	-4.767***
DLY Cyprus	0.059 (0.012)	4.794***
DLY Bosnia and Herzegovina	-0.208 (0.059)	-3.515***
DLY Portugal (Lisboa FIR)	-0.076 (0.029)	-2.579**
DLY Czech Republic	-0.041 (0.018)	-2.303**
DLY Sweden	-0.167 (0.078)	-2.141**

Bulgaria, adjusted R^2: 0.312		
Variable	Coefficient (Std. Error)	t value
Intercept	2.476 (0.015)	166.061***
DLY Hungary	0.169 (0.014)	12.079***
DLY Bosnia and Herzegovina	0.25 (0.055)	4.581***
DLY Poland	0.093 (0.011)	8.626***
DLY Slovakia	-0.343 (0.054)	-6.333***
DLY Cyprus	-0.05 (0.011)	-4.628***
DLY Belgium	-0.088 (0.02)	-4.454***
DLY Romania	0.177 (0.047)	3.769***
DLY Germany	0.055 (0.012)	4.466***
DLY Estonia	-0.479 (0.121)	-3.97***
DLY Serbia and Montenegro	0.073 (0.02)	3.712***
DLY Spain (Canarias)	-0.033 (0.012)	-2.761**
DLY Denmark	-0.409 (0.174)	-2.351**
DLY Netherlands	-0.137 (0.06)	-2.278**
DLY Portugal (Lisboa FIR)	-0.047 (0.023)	-1.999**

Croatia, adjusted R^2: 0.368		
Variable	Coefficient (Std. Error)	t value
Intercept	1.397 (0.007)	188.89***
DLY Croatia	0.14 (0.013)	10.464***
DLY Hungary	0.048 (0.009)	5.119***
DLY Austria	0.047 (0.009)	5.232***
DLY Serbia and Montenegro	0.041 (0.011)	3.823***
DLY France	0.011 (0.003)	3.492***
DLY Spain (Canarias)	-0.022 (0.006)	-3.728***
DLY Greece	-0.039 (0.012)	-3.276**
DLY Switzerland	0.039 (0.015)	2.642**
DLY Sweden	-0.092 (0.034)	-2.727**
DLY Bosnia and Herzegovina	-0.084 (0.029)	-2.931**
DLY Italy	0.064 (0.028)	2.292**
DLY Netherlands	0.056 (0.028)	2.026**

Cyprus, adjusted R^2: 0.052		
Variable	Coefficient (Std. Error)	t value
Intercept	4.261 (0.019)	227.246***
DLY Croatia	0.083 (0.026)	3.233**
DLY Cyprus	0.039 (0.014)	2.757**
DLY France	-0.023 (0.008)	-2.92**
DLY Greece	0.102 (0.03)	3.402***
DLY Norway	-0.57 (0.281)	-2.033**
DLY Portugal (Lisboa FIR)	-0.1 (0.031)	-3.206**
DLY Spain (Canarias)	-0.06 (0.016)	-3.728***

Czech Republic, adjusted R^2: 0.543		
Variable	Coefficient (Std. Error)	t value
Intercept	2.083 (0.009)	239.357***
DLY Austria	0.086 (0.01)	8.38***
DLY Cyprus	0.021 (0.006)	3.365***
DLY Czech Republic	0.026 (0.009)	3.007**
DLY Estonia	-0.15 (0.071)	-2.104**
DLY France	-0.008 (0.004)	-2.02**
DLY Germany	0.141 (0.008)	17.277***
DLY Hungary	0.062 (0.01)	6.213***
DLY Italy	0.094 (0.031)	3.058**
DLY Poland	0.055 (0.007)	8.463***
DLY Serbia and Montenegro	-0.038 (0.011)	-3.347***
DLY Slovakia	-0.081 (0.035)	-2.343**

Denmark, adjusted R^2: 0.101		
Variable	Coefficient (Std. Error)	t value
Intercept	1.086 (0.008)	137.274***
DLY $_{Croatia}$	0.022 (0.01)	2.094**
DLY $_{Germany}$	0.035 (0.006)	5.953***
DLY $_{Netherlands}$	0.146 (0.029)	5.026***
DLY $_{Poland}$	0.023 (0.006)	4.033***
DLY $_{Slovakia}$	-0.085 (0.029)	-2.916**
DLY $_{Spain (Canarias)}$	-0.016 (0.006)	-2.516**
DLY $_{Sweden}$	0.072 (0.034)	2.105**

Estonia, adjusted R^2: 0.676		
Variable	Coefficient (Std. Error)	t value
Intercept	1.401 (0.029)	49.032***
DLY $_{Bosnia and Herzegovina}$	1.809 (0.111)	16.301***
DLY $_{Poland}$	0.344 (0.022)	15.94***
DLY $_{Germany}$	0.431 (0.029)	14.705***
DLY $_{Belgium}$	-0.325 (0.04)	-8.163***
DLY $_{Serbia and Montenegro}$	0.319 (0.04)	8.028***
DLY $_{Austria}$	-0.183 (0.032)	-5.738***
DLY $_{Czech Republic}$	0.132 (0.029)	4.526***
DLY $_{Estonia}$	-0.844 (0.236)	-3.581***
DLY $_{Italy}$	0.371 (0.103)	3.583***
DLY $_{France}$	-0.044 (0.013)	-3.419***
DLY $_{Cyprus}$	-0.081 (0.021)	-3.797***
DLY $_{Croatia}$	0.125 (0.046)	2.705**
DLY $_{Slovakia}$	-0.402 (0.115)	-3.503***
DLY $_{UK (Continental)}$	0.218 (0.068)	3.223**
DLY $_{North Macedonia}$	0.203 (0.098)	2.081**
DLY $_{Netherlands}$	-0.24 (0.121)	-1.977**

Finland, adjusted R^2: 0.525		
Variable	Coefficient (Std. Error)	t value
Intercept	0.983 (0.026)	37.918***
DLY $_{Bosnia and Herzegovina}$	1.419 (0.097)	14.635***
DLY $_{Czech Republic}$	0.127 (0.026)	4.883***
DLY $_{Poland}$	0.168 (0.019)	8.619***
DLY $_{Serbia and Montenegro}$	0.228 (0.035)	6.469***
DLY $_{Germany}$	0.268 (0.026)	10.222***
DLY $_{Belgium}$	-0.195 (0.033)	-5.945***
DLY $_{Austria}$	-0.151 (0.029)	-5.188***
DLY $_{Greece}$	-0.134 (0.039)	-3.421***
DLY $_{Hungary}$	0.084 (0.029)	2.868**
DLY $_{Cyprus}$	-0.046 (0.019)	-2.437**
DLY $_{France}$	-0.024 (0.012)	-2.078**

France, adjusted R^2: 0.257		
Variable	Coefficient (Std. Error)	t value
Intercept	3.215 (0.009)	367.888***
DLY $_{France}$	0.04 (0.004)	10.229***
DLY $_{Belgium}$	0.052 (0.011)	4.929***
DLY $_{Spain\ (Canarias)}$	-0.056 (0.008)	-6.77***
DLY $_{Switzerland}$	0.069 (0.018)	3.849***
DLY $_{Portugal\ (Lisboa\ FIR)}$	-0.055 (0.014)	-3.901***
DLY $_{Germany}$	0.028 (0.008)	3.749***
DLY $_{Spain\ (Continental)}$	0.041 (0.011)	3.712***
DLY $_{Serbia\ and\ Montenegro}$	-0.034 (0.01)	-3.42***
DLY $_{Sweden}$	-0.102 (0.037)	-2.729**
DLY $_{UK\ (Continental)}$	0.047 (0.02)	2.379**

Germany, adjusted R^2: 0.512		
Variable	Coefficient (Std. Error)	t value
Intercept	2.324 (0.011)	209.334***
DLY $_{Germany}$	0.229 (0.011)	21.421***
DLY $_{Austria}$	0.044 (0.013)	3.371***
DLY $_{Netherlands}$	0.253 (0.041)	6.16***
DLY $_{Czech\ Republic}$	-0.054 (0.011)	-4.98***
DLY $_{Cyprus}$	0.037 (0.008)	4.626***
DLY $_{Poland}$	0.03 (0.008)	3.656***
DLY $_{Bosnia\ and\ Herzegovina}$	-0.117 (0.04)	-2.907**
DLY $_{Estonia}$	-0.206 (0.09)	-2.29**
DLY $_{Portugal\ (Lisboa\ FIR)}$	0.05 (0.016)	3.038**
DLY $_{Slovakia}$	-0.106 (0.044)	-2.405**
DLY $_{France}$	0.015 (0.005)	3.126**
DLY $_{Hungary}$	0.037 (0.013)	2.984**
DLY $_{Serbia\ and\ Montenegro}$	-0.03 (0.015)	-1.983**
DLY $_{Greece}$	-0.034 (0.017)	-1.97**

Greece, adjusted R2: 0.130		
Variable	Coefficient (Std. Error)	t value
Intercept	2.461 (0.014)	176.199***
DLY $_{Spain\ (Canarias)}$	-0.071 (0.011)	-6.312***
DLY $_{Serbia\ and\ Montenegro}$	0.091 (0.016)	5.648***
DLY $_{Portugal\ (Lisboa\ FIR)}$	-0.14 (0.022)	-6.458***
DLY $_{Germany}$	-0.044 (0.012)	-3.655***
DLY $_{Croatia}$	0.08 (0.02)	3.997***
DLY $_{Cyprus}$	-0.044 (0.01)	-4.49***
DLY $_{Poland}$	-0.036 (0.01)	-3.577***
DLY $_{Czech\ Republic}$	0.042 (0.014)	3.121**
DLY $_{Greece}$	0.076 (0.021)	3.57***
DLY $_{France}$	-0.016 (0.006)	-2.613**
DLY $_{Bulgaria}$	1.651 (0.75)	2.202**
DLY $_{Slovakia}$	-0.103 (0.052)	-1.985**

Hungary, adjusted R^2: 0.414		
Variable	Coefficient (Std. Error)	t value
Intercept	1.509 (0.01)	152.264***
DLY Germany	0.095 (0.009)	11.154***
DLY Hungary	0.089 (0.011)	7.879***
DLY Poland	0.081 (0.007)	11.312***
DLY Belgium	-0.073 (0.012)	-5.934***
DLY Serbia and Montenegro	0.052 (0.013)	3.946***
DLY Cyprus	-0.03 (0.007)	-4.165***
DLY Spain (Canarias)	-0.026 (0.008)	-3.354***
DLY Austria	0.043 (0.011)	3.822***
DLY Bosnia and Herzegovina	0.111 (0.037)	3.02**
DLY Greece	0.049 (0.015)	3.286**
DLY Estonia	-0.213 (0.081)	-2.616**
DLY France	-0.01 (0.004)	-2.322**
DLY Sweden	-0.095 (0.043)	-2.209**

Ireland, adjusted R^2: 0.052		
Variable	Coefficient (Std. Error)	t value
Intercept	1.088 (0.009)	124.4***
DLY France	0.021 (0.004)	5.431***
DLY Belgium	0.034 (0.01)	3.265**
DLY Portugal (Lisboa FIR)	0.052 (0.014)	3.699***
DLY Cyprus	0.018 (0.006)	2.895**

Italy, adjusted R^2: 0.290		
Variable	Coefficient (Std. Error)	t value
Intercept	2.879 (0.011)	261.892***
DLY France	0.068 (0.005)	13.834***
DLY Austria	0.04 (0.013)	3.034**
DLY Spain (Canarias)	-0.053 (0.009)	-5.916***
DLY Italy	0.216 (0.041)	5.301***
DLY Belgium	0.072 (0.013)	5.442***
DLY Greece	-0.078 (0.018)	-4.437***
DLY Croatia	0.057 (0.02)	2.89**
DLY Switzerland	0.09 (0.022)	4.132***
DLY Serbia and Montenegro	-0.045 (0.015)	-3.063**
DLY Sweden	-0.13 (0.05)	-2.585**
DLY Hungary	0.031 (0.014)	2.269**
DLY Ireland	0.406 (0.18)	2.257**

Latvia, adjusted R^2: 0.647		
Variable	Coefficient (Std. Error)	t value
Intercept	1.478 (0.036)	41.177***
DLY Bosnia and Herzegovina	2.213 (0.137)	16.13***
DLY Poland	0.438 (0.027)	16.185***
DLY Czech Republic	0.172 (0.036)	4.721***
DLY Serbia and Montenegro	0.397 (0.049)	8.086***
DLY Austria	-0.195 (0.036)	-5.376***
DLY Germany	0.484 (0.037)	13.242***
DLY Belgium	-0.427 (0.047)	-9.152***
DLY Cyprus	-0.101 (0.026)	-3.863***
DLY Estonia	-1.04 (0.296)	-3.514***
DLY France	-0.048 (0.016)	-3**
DLY Italy	0.386 (0.13)	2.976**
DLY Slovakia	-0.42 (0.144)	-2.912**
DLY UK (Continental)	0.201 (0.082)	2.451**
DLY North Macedonia	0.281 (0.122)	2.308**

Lithuania, adjusted R^2: 0.660		
Variable	Coefficient (Std. Error)	t value
Intercept	2.471 (0.071)	34.622***
DLY Bosnia and Herzegovina	4.343 (0.27)	16.06***
DLY Poland	0.909 (0.053)	17.018***
DLY Czech Republic	0.358 (0.072)	4.995***
DLY Austria	-0.461 (0.072)	-6.407***
DLY Germany	1.078 (0.072)	14.991***
DLY Belgium	-0.942 (0.092)	-10.227***
DLY Serbia and Montenegro	0.678 (0.095)	7.136***
DLY Cyprus	-0.221 (0.052)	-4.281***
DLY Estonia	-2.189 (0.581)	-3.77***
DLY France	-0.089 (0.032)	-2.774**
DLY UK (Continental)	0.471 (0.162)	2.911**
DLY Italy	0.677 (0.255)	2.656**
DLY Slovakia	-0.671 (0.282)	-2.374**
DLY Spain (Continental)	-0.153 (0.077)	-1.989**

Malta, adjusted R^2: 0.230		
Variable	Coefficient (Std. Error)	t value
Intercept	2.626 (0.026)	99.573***
DLY Germany	-0.247 (0.023)	-10.931***
DLY Cyprus	-0.103 (0.018)	-5.789***
DLY Spain (Canarias)	-0.072 (0.021)	-3.402***
DLY Belgium	-0.119 (0.031)	-3.803***
DLY Portugal (Lisboa FIR)	-0.145 (0.041)	-3.521***
DLY Estonia	-0.604 (0.209)	-2.888**
DLY Poland	-0.052 (0.019)	-2.688**
DLY Czech Republic	0.053 (0.026)	2.084**

Netherlands, adjusted R^2: 0.196		
Variable	Coefficient (Std. Error)	t value
Intercept	2.689 (0.018)	145.817***
DLY $_{Germany}$	0.156 (0.016)	9.997***
DLY $_{Netherlands}$	0.374 (0.068)	5.485***
DLY $_{Poland}$	0.084 (0.014)	6.138***
DLY $_{Cyprus}$	0.049 (0.013)	3.724***
DLY $_{Slovakia}$	-0.297 (0.071)	-4.18***
DLY $_{Austria}$	0.06 (0.018)	3.281**
DLY $_{Czech\ Republic}$	-0.057 (0.018)	-3.18**
DLY $_{Spain\ (Canarias)}$	-0.044 (0.014)	-3.075**
DLY $_{Estonia}$	-0.348 (0.148)	-2.349**

Norway, adjusted R^2: 0.110		
Variable	Coefficient (Std. Error)	t value
Intercept	1.561 (0.017)	93.913***
DLY $_{Hungary}$	0.148 (0.016)	9.195***
DLY $_{Serbia\ and\ Montenegro}$	-0.108 (0.022)	-4.798***
DLY $_{Greece}$	-0.092 (0.026)	-3.548***
DLY $_{Germany}$	-0.03 (0.012)	-2.463**
DLY $_{Cyprus}$	0.052 (0.012)	4.277***
DLY $_{Estonia}$	-0.517 (0.138)	-3.741***
DLY $_{Malta}$	3.084 (0.973)	3.17**
DLY $_{Ireland}$	0.674 (0.259)	2.607**
DLY $_{Bosnia\ and\ Herzegovina}$	-0.142 (0.061)	-2.329**
DLY $_{Slovakia}$	-0.151 (0.063)	-2.399**
DLY $_{Poland}$	-0.024 (0.012)	-1.974**

Poland, adjusted R^2: 0.514		
Variable	Coefficient (Std. Error)	t value
Intercept	2.018 (0.027)	75.384***
DLY $_{Poland}$	0.429 (0.02)	21.79***
DLY $_{Bosnia\ and\ Herzegovina}$	0.815 (0.098)	8.307***
DLY $_{Czech\ Republic}$	0.066 (0.027)	2.483**
DLY $_{Belgium}$	-0.256 (0.033)	-7.694***
DLY $_{Germany}$	0.285 (0.026)	10.901***
DLY $_{Cyprus}$	-0.074 (0.019)	-3.907***
DLY $_{Spain\ (Continental)}$	-0.075 (0.029)	-2.567**
DLY $_{Serbia\ and\ Montenegro}$	0.151 (0.034)	4.389***
DLY $_{Slovakia}$	-0.197 (0.104)	-1.891*
DLY $_{Estonia}$	-0.63 (0.214)	-2.938**
DLY $_{Austria}$	-0.073 (0.027)	-2.735**
DLY $_{Portugal\ (Lisboa\ FIR)}$	-0.101 (0.041)	-2.445**
DLY $_{France}$	-0.024 (0.012)	-2.022**

Portugal Continental, adjusted R^2: 0.044		
Variable	Coefficient (Std. Error)	t value
Intercept	1.777 (0.013)	137.164***
DLY $_{France}$	0.035 (0.006)	6.316***
DLY $_{Bosnia\ and\ Herzegovina}$	-0.157 (0.05)	-3.139**
DLY $_{Hungary}$	0.047 (0.012)	4.008***
DLY $_{Slovakia}$	-0.141 (0.051)	-2.786**
DLY $_{Poland}$	-0.026 (0.01)	-2.623**
DLY $_{Serbia\ and\ Montenegro}$	-0.044 (0.019)	-2.377**

Romania, adjusted R^2: 0.396		
Variable	Coefficient (Std. Error)	t value
Intercept	2.161 (0.015)	140.132***
DLY $_{Hungary}$	0.181 (0.014)	12.526***
DLY $_{Poland}$	0.139 (0.011)	12.469***
DLY $_{Bosnia\ and\ Herzegovina}$	0.296 (0.056)	5.246***
DLY $_{Belgium}$	-0.115 (0.02)	-5.626***
DLY $_{Slovakia}$	-0.328 (0.056)	-5.899***
DLY $_{Serbia\ and\ Montenegro}$	0.112 (0.02)	5.522***
DLY $_{Germany}$	0.075 (0.013)	5.938***
DLY $_{Cyprus}$	-0.045 (0.011)	-4.091***
DLY $_{Spain\ (Canarias)}$	-0.036 (0.012)	-2.924**
DLY $_{Estonia}$	-0.471 (0.125)	-3.775***
DLY $_{Portugal\ (Lisboa\ FIR)}$	-0.062 (0.024)	-2.547**
DLY $_{Denmark}$	-0.407 (0.18)	-2.262**
DLY $_{Netherlands}$	-0.123 (0.062)	-1.985**

Slovakia, adjusted R^2: 0.431		
Variable	Coefficient (Std. Error)	t value
Intercept	2.327 (0.018)	127.544***
DLY $_{Poland}$	0.236 (0.014)	17.293***
DLY $_{Germany}$	0.151 (0.018)	8.192***
DLY $_{Bosnia\ and\ Herzegovina}$	0.375 (0.06)	6.255***
DLY $_{Hungary}$	0.155 (0.017)	9.253***
DLY $_{Belgium}$	-0.119 (0.023)	-5.218***
DLY $_{Estonia}$	-0.516 (0.149)	-3.478***
DLY $_{Cyprus}$	-0.039 (0.013)	-2.961**
DLY $_{France}$	-0.02 (0.008)	-2.447**
DLY $_{Czech\ Republic}$	0.049 (0.018)	2.691**
DLY $_{Spain\ (Continental)}$	-0.046 (0.02)	-2.324**

Slovenia, adjusted R^2: 0.457		
Variable	Coefficient (Std. Error)	t value
Intercept	1.47 (0.009)	156.361***
DLY $_{Croatia}$	0.13 (0.016)	8.209***
DLY $_{Austria}$	0.118 (0.01)	11.38***
DLY $_{Germany}$	0.044 (0.008)	5.497***
DLY $_{Italy}$	0.141 (0.032)	4.368***
DLY $_{Switzerland}$	0.065 (0.019)	3.355***
DLY $_{Netherlands}$	0.101 (0.035)	2.919**
DLY $_{Hungary}$	0.036 (0.011)	3.222**
DLY $_{Spain (Canarias)}$	-0.019 (0.007)	-2.601**
DLY $_{Cyprus}$	-0.015 (0.007)	-2.187**
DLY $_{Sweden}$	-0.092 (0.041)	-2.248**
DLY $_{France}$	0.009 (0.004)	2.172**

Spain Canarias, adjusted R^2: 0.112		
Variable	Coefficient (Std. Error)	t value
Intercept	2.309 (0.018)	126.364***
DLY $_{Spain (Canarias)}$	0.127 (0.018)	7.128***
DLY $_{Hungary}$	-0.129 (0.017)	-7.751***
DLY $_{France}$	0.034 (0.008)	4.306***
DLY $_{Netherlands}$	0.262 (0.066)	3.935***
DLY $_{Slovakia}$	0.2 (0.069)	2.915**
DLY $_{Estonia}$	0.452 (0.152)	2.97**
DLY $_{Portugal (Lisboa FIR)}$	0.11 (0.03)	3.647***
DLY $_{Spain (Continental)}$	-0.081 (0.024)	-3.333***
DLY $_{Cyprus}$	0.026 (0.014)	1.925*
DLY $_{Italy}$	0.173 (0.066)	2.629**
DLY $_{Bosnia and Herzegovina}$	-0.128 (0.061)	-2.094**

Spain Continental, adjusted R^2: 0.396		
Variable	Coefficient (Std. Error)	t value
Intercept	3.305 (0.013)	249.167***
DLY $_{France}$	0.065 (0.006)	10.974***
DLY $_{Belgium}$	0.112 (0.016)	7.113***
DLY $_{Hungary}$	0.044 (0.013)	3.466***
DLY $_{Spain (Continental)}$	0.16 (0.017)	9.411***
DLY $_{Spain (Canarias)}$	-0.078 (0.012)	-6.41***
DLY $_{Cyprus}$	0.059 (0.009)	6.322***
DLY $_{Germany}$	0.072 (0.01)	6.907***
DLY $_{Serbia and Montenegro}$	-0.058 (0.016)	-3.731***
DLY $_{Sweden}$	-0.149 (0.057)	-2.606**

Sweden, adjusted R^2: 0.405		
Variable	Coefficient (Std. Error)	t value
Intercept	1.077 (0.009)	120.824***
DLY $_{Germany}$	0.113 (0.008)	13.948***
DLY $_{Poland}$	0.091 (0.007)	13.714***
DLY $_{Bosnia\ and\ Herzegovina}$	0.245 (0.03)	8.137***
DLY $_{Sweden}$	0.162 (0.04)	4.074***
DLY $_{Romania}$	-0.065 (0.028)	-2.284**
DLY $_{Switzerland}$	-0.043 (0.019)	-2.291**
DLY $_{France}$	-0.007 (0.004)	-1.805*
DLY $_{Hungary}$	0.031 (0.01)	3.193**
DLY $_{Austria}$	-0.028 (0.01)	-2.802**

Switzerland, adjusted R^2: 0.287		
Variable	Coefficient (Std. Error)	t value
Intercept	4.082 (0.019)	213.747***
DLY $_{Germany}$	0.128 (0.016)	8.117***
DLY $_{France}$	0.093 (0.008)	11.099***
DLY $_{Switzerland}$	0.208 (0.038)	5.418***
DLY $_{Greece}$	-0.13 (0.028)	-4.668***
DLY $_{Malta}$	5.091 (1.095)	4.65***
DLY $_{Ireland}$	1.048 (0.292)	3.59***
DLY $_{Cyprus}$	0.042 (0.013)	3.323***
DLY $_{Spain\ (Canarias)}$	-0.053 (0.015)	-3.467***
DLY $_{Serbia\ and\ Montenegro}$	-0.061 (0.021)	-2.883**
DLY $_{Poland}$	0.032 (0.014)	2.379**
DLY $_{Portugal\ (Lisboa\ FIR)}$	0.068 (0.03)	2.284**
DLY $_{Sweden}$	-0.159 (0.079)	-1.998**

Table 4 – Results of Model_3b (Source: PRB elaboration).

4 FLIGHT TRAJECTORY CASE STUDIES

46 This section presents a set of case studies aiming to illustrate the interdependency between the environment and capacity KPA analysis of trajectories on certain days. The case studies were conducted to further explore some of the findings of the statistical analysis (i.e. to provide some insight into the mechanisms behind the quantified results).

47 Case studies are defined based on the following key aspects:

- Impact on HFE of other Member States;
- Impact on local HFE received from other Member States; and
- Strength of the regression model (R^2 value).

48 Further to this, the selection also considered the following operational factors (to the extent possible):

- Level of FRA implementation in the Member State;
- Historical Level of local average en route ATFM delay;
- Dominant delay cause; and
- Military activity.[8]

49 Following this approach, the Member States selected for the case studies were: Estonia, Cyprus, and Spain Canarias.

50 A key part of the case studies is to provide a deeper understanding of how flight trajectories were affected by capacity underperformance. To this end, the major traffic flows impacted by the Member State in question were identified and translated into representative city pairs, to the maximum extent possible. This allowed a comparison of the trajectories of typical flights in the respective Member States under different circumstances (e.g. on days with high levels of en route ATFM delays compared to days with low levels of en route ATFM delays). The use of typical city pairs also enabled more in-depth analysis of both the capacity performance and the environmental performance associated with those flights.

51 Given that the main objective of the case studies was to examine trajectories in greater detail, the time scope of the analyses was limited to specific days, which were characteristic of: 1) Inefficient HFE, 2) high levels of en route ATFM delays, and 3) relatively efficient HFE combined with low delay levels (compared to average). All days were chosen from the years 2018 and 2019 as these years were most representative of a pre-pandemic traffic scenario.

4.1 Case study of Estonia

52 The FIR of Estonia lies at the junction of two main traffic flows: A North-East – South-West flow connecting major European hub airports with Chinese, South-Korean and other Asian airports, and a north-south flow connecting Estonia and Finland with other parts of Europe. There is also a third, less dominant North-West / South-East flow. These major flows are illustrated in Figure 1.

Figure 1 – The FIR of Estonia and the major traffic flows (Source: NEST tool of Eurocontrol).

53 For the case of Estonia, the State-level regression (Model 3b) included 16 States as explanatory variables, out of which the following were considered for the selection of the dates:

- Bosnia and Herzegovina;
- Germany;
- Italy;
- Poland;
- Serbia and Montenegro;
- Poland;
- Estonia (negative coefficient);
- Slovakia (negative coefficient); and

[8] Approximated by the estimated size of the air force (i.e. number of fighter aircraft), proximity to publicly known geopolitical hot-spots, and the relative size of the airspace.

- Belgium (negative coefficient).

54 The case study focused the analysis on three keys dates:

- 6th July 2019, when local HFE was high (inefficient);
- 28th July 2018, when the en route ATFM delays in the States affecting the State-level regression model were high; and
- 2nd November 2019, when the HFE was low (efficient) in Estonia and there were no delays.

55 For the three days selected, the additional distance flown and the associated HFE were calculated for each flight crossing the Estonian FIR. This enabled the calculation of the contribution of each flight to the horizontal flight inefficiency.

4.1.1.1 Day when local HFE was inefficient

56 On the 6th July 2019, the aircraft flew an additional 1.62 nautical miles on average, compared to the great circle distance (249% more than on the reference day). The average fuel burn per flight was 493 kilograms which correspond to 1.55 tons of CO_2 emissions.[9] Average fuel burn per flight and associated emissions were 12% lower than on the reference day, despite the route extensions being higher. This is related to the fact that in comparison to the reference day, flights were on average 3% shorter and the share of arrivals and departures to and from Estonian airports, which operate with less optimal fuel consumption, than overflights, was also lower.

57 The top ten city pairs which contributed the most to HFE deterioration in terms of additional distance flown were typically arrivals to Helsinki-Vantaa airport from various European cities, and the city pair of St. Petersburg – Antalya. The overview of the trajectories for these city pairs is shown in Figure 2.

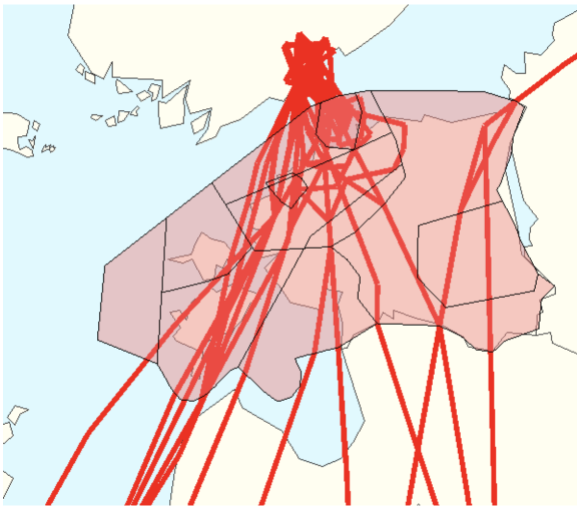

Figure 2 – City pairs with the highest additional distance on 6th July 2019 (Source: NEST tool of Eurocontrol).

4.1.1.2 Day when delays in the States affecting the State-level regression model were high

58 On the 28th July 2018, the aircraft flew an additional 0.76 nautical miles on average, compared to the great circle distance (64% more than on the reference day). The average fuel burn per flight was 579 kilograms which corresponds to 1.82 tons of CO_2 emission. The average fuel burn per flight and associated emissions were 4% higher than on the reference day. The share of local arrivals and departures was also the highest out of the three examined days.

59 The top ten city pairs, which contributed the most to horizontal flight inefficiency in terms of additional distance flown were as follows:

- Shanghai – London;
- Beijing – Amsterdam;
- Seoul – Paris;
- Beijing – London;
- St. Petersburg – Rimini;
- Hong Kong – London;
- Riga – Helsinki;
- Seoul – Amsterdam; and
- Frankfurt am Main – Helsinki.

60 The trajectories of the flights between these city pairs are summarised in Figure 3 (next page).

[9] Fuel burn was modelled based on the Eurocontrol Base of Aircraft Data (BADA), considering trajectory data and aircraft type. CO_2 emissions were computed from fuel burn with the application of the standard coefficient of 3.15kg of CO_2/kg of fuel burn.

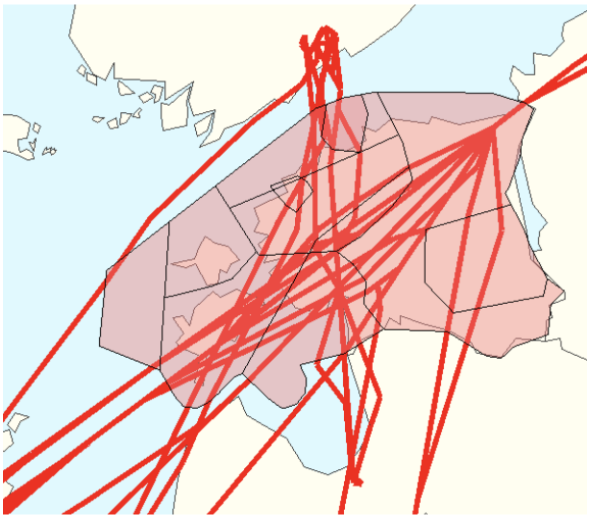

Figure 3 – City pairs with the highest additional distance on 28th July 2018 (Source: NEST tool of Eurocontrol).

4.1.1.3 Day when the HFE was low and there were no delays

61 On 2nd November 2019, aircraft flew an additional distance of 0.46 nautical miles on average, with an average fuel burn of 557 kilograms per flight and 1.75 tons of average CO_2 emission per flight. Local departures and arrivals had a slightly smaller share than on the day with relatively high delays, but still a higher share compared to the day with inefficient HFE. The top ten city pairs with the highest route extensions were:

- St. Petersburg – Antalya;
- Visby – Kuressaare;
- St. Petersburg – Khrabrovo (Kaliningrad);
- Shanghai – Amsterdam;
- Cannes-Mandelieu – Kuressaare;
- Helsinki – Monastir;
- Moscow – Helsinki;
- Tallinn – Bern;
- Helsinki – Istanbul; and
- Berlin – Helsinki.

62 Compared to the other two dates, flights departing from or arriving to Estonia contributed relatively more (although in absolute terms, these contributions were still low), and the share of long-haul, intercontinental flights also was lower. Flight trajectories from the top ten city pairs for the reference date are shown on Figure 4.

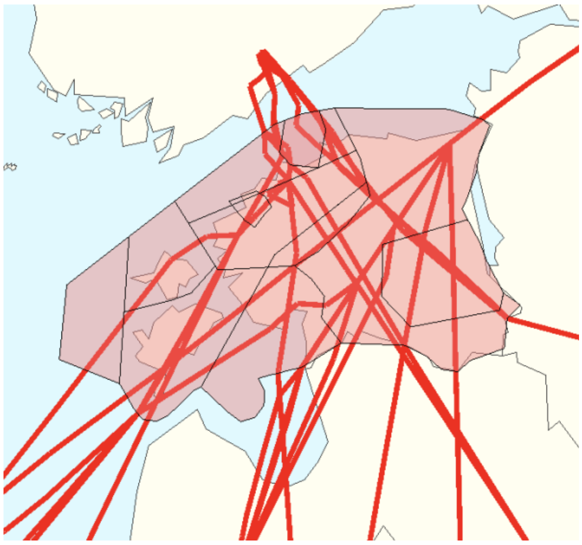

Figure 4 – City pairs with the highest additional distance on 2nd November 2019 (Source: NEST tool of Eurocontrol).

4.1.1.4 Individual flight contribution to delay and HFE

63 Further to looking into the trajectories of the most relevant city pairs, Figure 5 shows the results of the comparison of the three dates. On the date with relatively high horizontal inefficiency, the route extensions were more concentrated: 10% of the flights were responsible for almost 80% of the additional distance, whereas on the other two dates this figure was around 65%. On all three days, 40 to 50% of flights generated the total amount of additional distance.

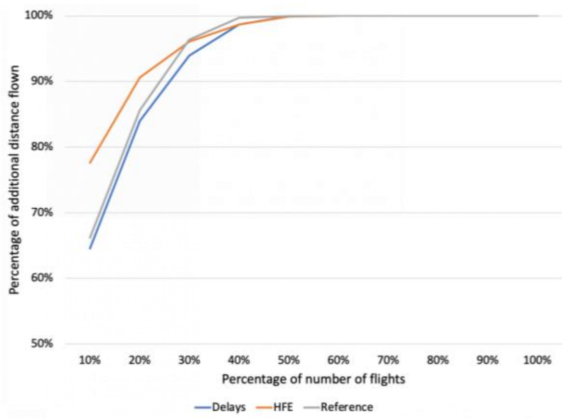

Figure 5 – Distribution of additional distance flown in Estonia, comparing the three dates (Source: PRB elaboration).

4.3 Case study of Cyprus

64 The Cyprus FIR is located at the South-Eastern corner of the SES area. Traffic flows to and from the large European hub airports, to and from Turkey, Africa, and the Middle East cross the airspace. Arrivals and departures to and from Beirut Rafic Hariri and Tel Aviv Ben Gurion airports also converge within the Cyprus FIR, further complicating the traffic. All these flows are shown on Figure 6.

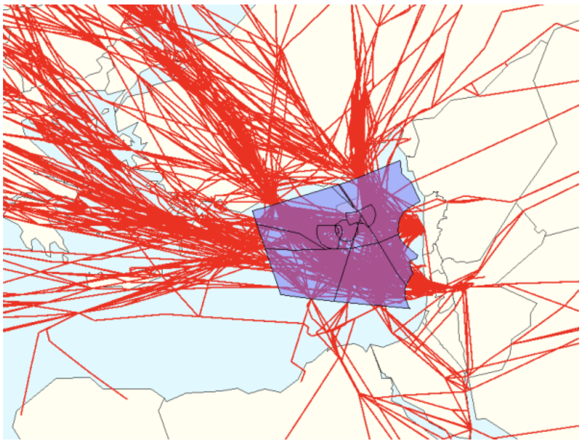

Figure 6 – The FIR of Cyprus and the major traffic flows (Source: NEST tool of Eurocontrol).

65 For the case of Cyprus, the FIR-level regression model included seven FIR-level delay variables as explanatory variables, out of out of which the following were considered for the selection of the dates:

- Cyprus;
- Croatia;
- Greece;
- Norway (negative coefficient); and
- Portugal (negative coefficient).

66 The case study considered the following dates:

- 18th July 2019, when local HFE was high (inefficient);
- 12th July 2019, when the en route ATFM delays in the States affecting the FIR level regression model were high; and
- 2nd December 2019, when the HFE of Cyprus was relatively low (efficient), and there were almost no delays.

67 The political situation between Turkey and Cyprus, military activities in the Sovereign Base Areas of Akrotiri and Dhekelia, as well as tensions between Cyprus and Turkey are likely key contributing factors to such inefficiencies.

4.3.1.1 Day when local HFE was inefficient

68 On 18th July 2019, an average 4.17 nautical miles of additional distance was flown by aircraft in Cyprus FIR (250% more than on the reference day). Aircraft burned 848 kilograms of fuel on an average flight, corresponding to 2.67 tons of CO_2 emissions per flight. The average fuel burn per flight and associated emissions were 15% higher than on the reference day. The share of local arrivals and departures was higher than on the reference day but slightly lower than on the day with high delays.

69 The top ten city pairs contributing to horizontal flight inefficiency were arrivals and departures to and from Tel Aviv and Beirut, and flights between Amman and Istanbul. Flights from the top ten city pairs are shown on Figure 7.

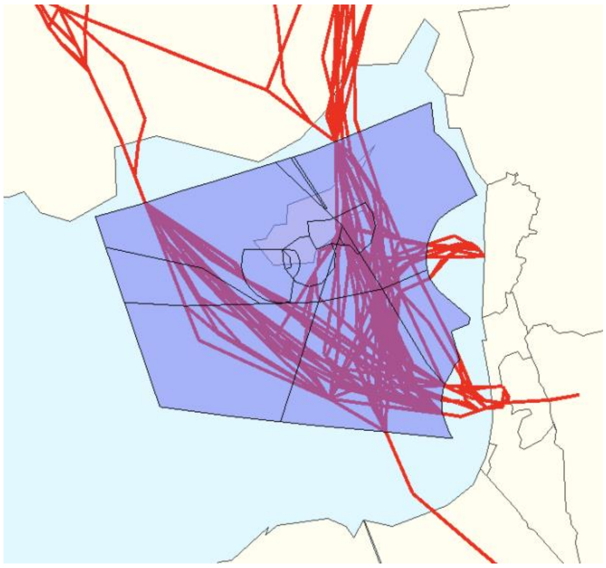

Figure 7 – City pairs with the highest additional distance on 18th July 2019 (Source: NEST tool of Eurocontrol).

4.3.1.2 Day when local delay was high

70 On 12th July 2019, a date with relatively high en route ATFM delays, aircraft flew an additional 2.65 nautical miles per flight in the FIR of Cyprus, compared to the great circle distance (123% more than on the reference day). The average fuel burn per flight on this day was 690 kilograms, associated with 2.17 tons of CO_2 emissions per flight. Both figures were 6% lower than on the reference day, despite the higher route extensions. The share of local departures and arrivals was the highest among the three days, so this could not explain why average fuel burn and CO_2 emissions were lower, however, flights on average were

shorter on the day with relatively high delays, explaining at least some of the difference in average fuel burn and emissions.

71 The top ten city pairs with the most additional distances on this date were:

- Tel Aviv – Antalya;
- Amman – Istanbul;
- Dubai – Larnaca;
- Amman – Beirut;
- Moscow – Larnaca;
- Sharjah – Beirut;
- Larnaca – Bucharest;
- Tel Aviv – Budapest;
- Tel Aviv – Vienna; and
- Kuwait – Beirut.

72 The key factors driving horizontal flight inefficiencies were the flights to and from Beirut and Tel Aviv (apart from the arrivals and departures of Larnaca). Flights departing from or arriving to Beirut circumnavigate the Israeli airspace, which results in deviations from the great circle distances, whereas flights between Tel Aviv and Istanbul tend to fly around Cyprus from the South, resulting in route extensions. Examples of these trajectories are shown in Figure 8.

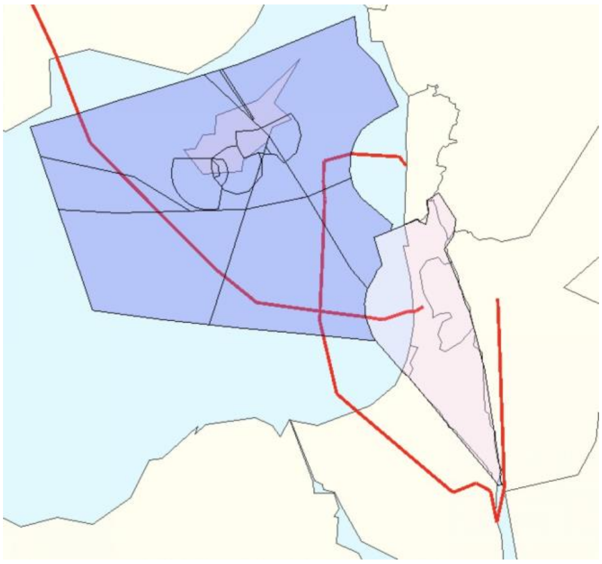

Figure 8 – Example of flights avoiding Israeli airspace in the FIR of Cyprus (flight from Amman to Beirut), and flights flying around Cyprus from the South between Tel Aviv and Istanbul (Source: NEST tool of Eurocontrol).

4.3.1.3 Day when the HFE and delays were low

73 On 2nd December 2019, the average additional distance flown in the Cyprus FIR was 1.19 nautical miles per flight. The average fuel burn per flight was 736 kilograms, corresponding to 2.32 tons of CO_2 emissions per flight. Both figures are higher than on the day with relatively high delays, and this could not be explained by local arrivals and departures, as the share of these flights was the lowest this day. A likely explanation for this anomaly is that on this day traffic to and from military airbases was more significant (see following paragraphs) which presumably involved aircraft which were less fuel efficient than modern civilian passenger carriers.

74 The top ten city pairs with highest additional distances flown on the reference day were:

- Tel Aviv – Istanbul;
- Camp Taji – Limassol;
- Dubai – Larnaca;
- Beirut – Cairo;
- Warsaw – Larnaca;
- Paphos – Be’er Sheva;
- Dubai – Beirut;
- Amman – Beirut;
- Paphos – Tel Aviv; and
- Moscow – Larnaca.

75 These city pairs are indicated on Figure 9. Interestingly, there were two city pairs in the top ten which are likely to represent military activities (between Camp Taji and Limassol and Paphos and Be’er Sheva), since with the exception of Paphos, these locations are hosting military airbases. Once again, flights to and from Beirut, Tel Aviv and Larnaca are strong contributors to horizontal flight inefficiency.

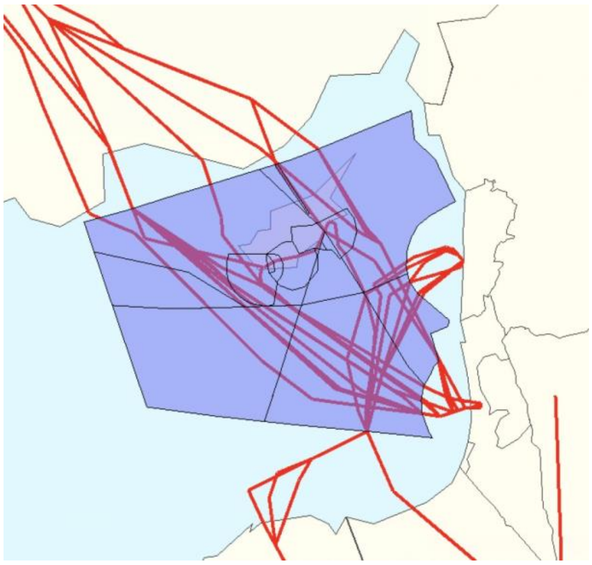

Figure 9 – City pairs with the highest additional distance on 12th July 2019 (Source: NEST tool of Eurocontrol).

4.3.1.4 Individual flight contribution to delay and HFE

76 When looking at the distribution of the route extension across the different flights, the case study found that on the reference dates fewer flights were responsible for the additional distance flown: 10% of the flights generated around 75% of the additional distance, and only 40% of the flights were responsible for all the additional distance. On the two other dates, route extensions were more distributed. The overview of the results is shown on Figure 10.

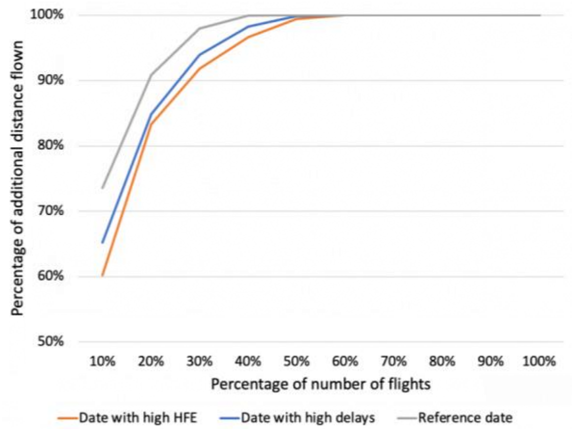

Figure 10 – Distribution of additional distance flown in Cyprus, comparing the three dates (Source: PRB elaboration).

4.4 Case study of Spain Canarias

77 The airspace of Spain Canarias is detached from the core European airspace, located to the South-West of Spain. The main traffic flows are flights from major European cities, combined with traffic from South America. The airspace and the traffic patterns are shown on Figure 11.

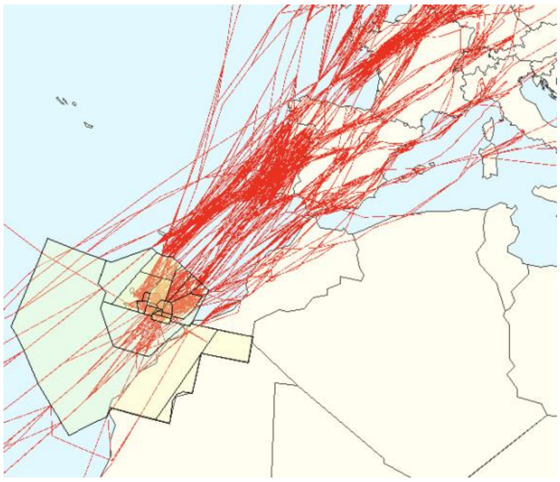

Figure 11 – Overview of the airspace and the main traffic flows of Spain Canarias (Source: NEST tool of Eurocontrol).

78 Due to the fact that en route ATFM delays in Spain Canarias showed up with a negative coefficient, as relevant and significant variables in many of the State-level regression models as well as in the Union-wide model, the selection of dates for the case study was different from the other cases. Different in that the Union-wide HFE was used to define days with relatively inefficient HFE, and the only delay variable considered for the selection of the date with relatively high delays was that of Spain Canarias. These altered criteria led to the selection of the following dates:

- 25th December 2018 as the reference day, when there were no delays in Spain Canarias, and the Union-wide HFE was relatively low (efficient);
- 1st July 2019, when horizontal flight inefficiency in the SES area was relatively high; and
- 21st December 2019, when en route ATFM delays in Spain Canarias were relatively high.

79 Since the additional distance flown in the Spain Canarias FIR was not relevant in this case study, as the focus was on the impact on the SES area, the analysis looked into how the trajectories were different on the three days. In order to identify the impact of delays in Spain Canarias on the Union-wide flight efficiency, traffic density maps were generated for the three specified dates.

4.4.1.1 Day when the HFE was low and there were no delays

80 On the reference date (Figure 12, next page), traffic density is high along the east-west and south-west – north-east axes, but other areas remain

less saturated. The area of Spain Canarias is moderately dense.[10] This reflects the lower number of flights over the day, compared to the other two days.

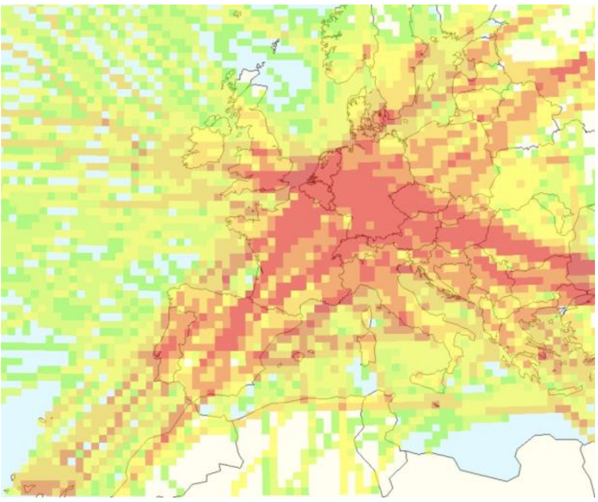

Figure 12 – Traffic density in Europe on the day without delays in Spain Canarias, and relatively low Union-wide horizontal flight inefficiency (Source: NEST tool of Eurocontrol).

4.4.1.2 Day when Union-wide HFE was inefficient

81 On the date when Union-wide flight inefficiency is relatively high (Figure 13), most of the European airspace appears to have high traffic density with some hot spots around major hub airports (London, Paris, Frankfurt am Main, Brussels, and Amsterdam). This is the representation of the increased traffic levels compared to the reference day. It is also understood that the more the traffic density increases around the hot spots and major flows, the harder it is to circumnavigate such areas, leading to worsening HFE.

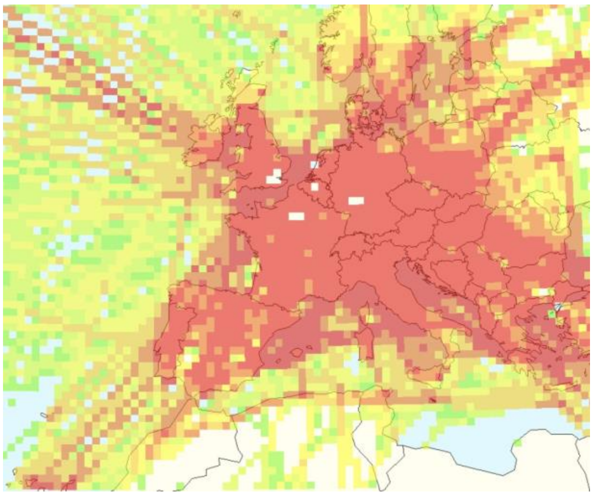

Figure 13 – Traffic density in Europe on the day with relatively high Union-wide horizontal flight inefficiency (Source: Nest tool of Eurocontrol).

4.4.1.3 Day when local delay was high

82 Finally, when looking at the day with relatively high delays in Spain Canarias (Figure 14), a shift in density over Europe can be observed: The airspace over and adjacent to Spain Canarias is denser with traffic, while the airspace over Spain, France, and Portugal has lower density (compared to the day with relatively high Union-wide flight inefficiency).

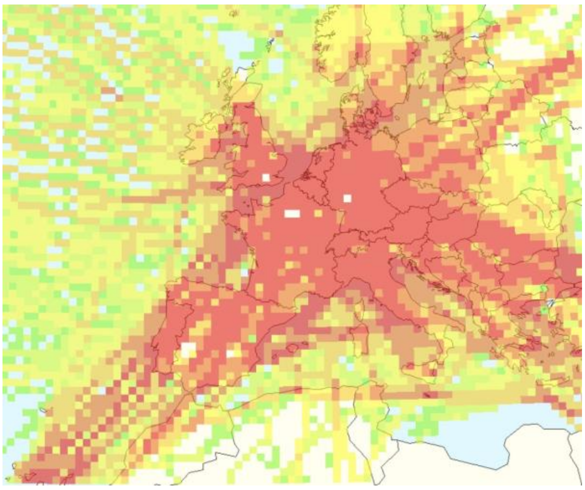

Figure 14 – Traffic density in Europe when en route ATFM delays in Spain Canarias are relatively high (Source: NEST Tool of Eurocontrol).

83 This indicates that en route ATFM delays in airspaces relatively far away from the core area of Europe reduce the density in the most complex and dense areas, and thus contribute to improving flight efficiency. This could explain why the en route ATFM delay variable in Spain Canarias was

[10] Traffic densitiy is measured as daily IFR movements in 30NM by 30NM cells. Red color corresponds to 200 or more movements per day.

significant despite a negative coefficient in the Union-wide regression model, and also in many FIR-level models as well.

84 The analysis of individual flight contribution to HFE and delay was not conducted for this case, due to the difference in the applied approach (individual trajectories and route extensions were not calculated).