UNIVERSITAT POLITÈCNICA DE CATALUNYA
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**Treball de Fi de Màster**

# MÀSTER UNIVERSITARI EN ENGINYERIA AERONÀUTICA

**APÈNDIXS**

# FREE ROUTING AIRSPACE IMPLEMENTATION IN SPAIN

**PRELIMINARY STUDY**

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# Acronyms

| | |
|---|---|
| ACC | Area Control Center |
| AMSL | Above Mean Sea Level |
| ARES | Area reservation/restriction |
| ATC | Air Traffic Control |
| ATCO | Air Traffic Controller Officer |
| ATFCM | Air Traffic Flow and Capacity Management |
| ATS | Air Traffic Service |
| DDR2 | Demand Data Repository 2 (EUROCONTROL) |
| FIR | Flight Information Region |
| FL | Flight Level |
| FRA | Free Route Airspace |
| IAS | Indicated Airspeed |
| ICAO | International Civil Aviation Organization |
| IFR | Instrumental Flight Rules |
| R-NEST | R - Network strategic modelling tool |
| SUA | Special Use of Airspace |
| TMA | Terminal Maneuvering Area |
| VFR | Visual Flight Rules |

# Appendix A: Spanish Airspace classification

| | | AIRSPACE CLASSIFICATION | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | CONTROLLED AIRSPACE | | | | | UNCONTROLLED AIRSPACE | |
| **CLASS** | | **A** | **B** | **C** | **D** | **E** | **F** | **G** |
| **IFR Flights allowed** | | X | X | X | X | X | X | X |
| **VFR Flights allowed** | | - | X | X | X | X | X | X |
| **Flights subject to ATS** | | X | X | X | X | IFR Only | - | - |
| **Flights subject to ATC authorization** | | X | X | X | X | IFR Only | - | - |
| **Flights separated by type** | **IFR Flights** | All | All | IFR flights separated with others IFR and VFR | IFR flights separated with IFR<br><br>IFR flights with other VFR receive:<br>-Traffic information<br>-Anticollision advisory under request | IFR Flights separated with IFR<br><br>IFR Flights with other VFR receive:<br>-Traffic information when possible | IFRs receive air traffic advisory service and All Flights receive flight information service under request | IFR and VFR flights receive flight information service under request |
| | **VFR Flights** | - | All | VFR Flights separated from | VFR flights with other IFR and VFR receive:<br>-Traffic information<br>-Anticollision advisory under request | VFR flights with other IFR and VFR receive:<br>-Traffic information when possible | IFR and VFR flights receive flight information service under request | |
| **Air-land continuous communication by voice required** | | X | X | X | X | Only IFR | Air-land continuous communication by voice required for IFR flights using air traffic advisory service.<br>All IFR flights must be in conditions to stablish air-land communication by voice | All IFR flights must be in conditions to stablish air-land communication by voice |
| **Velocity limitations** | | - | - | VFR: 250kts IAS under 3050m AMSL (10000ft), except when approved by competent authority for aircrafts not able to maintain the limitation for technical or safety reasons | IFR / VFR: 250kts IAS under 3050m AMSL (10000ft), except when approved by competent authority for aircrafts not able to maintain the limitation for technical or safety reasons | | | |

*Table 1. Airspace characteristics by class in Spain*[1]

[1] Table elaborated with information extracted from ENAIRE

# Appendix B: Description of the RStudio Scripts developed

## Raw data filter

The functionality of the first script is to read a raw data file .so6 in the DDR2 format and transform the data in a list, separating route data from flight data and navpoints information. This script is originally developed by prof. Oriol Lordan.

Firstly, it eliminates flights departing from or arriving to airports with “ZZZZ” or “AFIL” designations, meaning airports without ICAO code or flight plan delivered with the aircraft in flight, respectively. Then, it filters flights by their airline, comparing callsign of each flight with ICAO current airline designators.

After that, it arranges conveniently time information and point information in order to start obtaining the desired information about flights and navpoints. Finally, for route data, it gets the cumulative distance between route points, an indicator for the flight status (cruise, ascending or descending) and a marker to distinguish between planned data or real flown data.

As in the studio only real data is going to be used, this marker is set to FALSE.

In the figure below, it can be seen the input data and the output data of this file:

```
                id fl_ori fl_des ac_type  time1  time2 FL1 FL2    call  date1  date2     lat1      lon1     lat2      lon2      fl_id     dist
      1:    ENXP_ENXV   ENXP   ENXV     S92  55700  55721   1   1 BHL175A 160412 160412 3484.700  114.6167 3484.633  113.3333 1500136103 0.681852
      2:    LOWI_LOWI   LOWI   LOWI    TB20  64300 114300  19  19   DEAOU 160412 160412 2835.617  680.6333 2835.617  680.6333 1500146103 0.000000
      3:    EFTP_EFTP   EFTP   EFTP    C295  70500 120500   4   4    K371 160412 160412 3684.917 1415.2667 3684.917 1415.2667 1500166103 0.000000
      4:    EFTP_EFTP   EFTP   EFTP    C295  70500 120500   4   4     K37 160412 160412 3684.917 1415.2667 3684.917 1415.2667 1500206103 0.000000
      5:    EPBY_EPBY   EPBY   EPBY    ZZZZ  70500 120500   2   2 TIGER03 160412 160412 3185.800 1078.6667 3185.800 1078.6667 1500226103 0.000000
     ---
6478773: $GtMy_*GRN1   LIRP   LEGE    B738 124750 124849  50  40 RYR31DH 160416 160416 2525.050  169.8167 2521.500  168.4333  195812034 3.695606
6478774: *GRN1_$GtMz   LIRP   LEGE    B738 124849 124908  40  35 RYR31DH 160416 160416 2521.500  168.4333 2520.433  168.0333  195812034 1.107292
6478775: $GtMz_$GtNA   LIRP   LEGE    B738 124908 124945  35  25 RYR31DH 160416 160416 2520.433  168.0333 2517.767  167.0333  195812034 2.768327
6478776: $GtNA_$GtNB   LIRP   LEGE    B738 124945 125005  25  20 RYR31DH 160416 160416 2517.767  167.0333 2517.250  166.8333  195812034 0.537647
6478777:  $GtNB_LEGE   LIRP   LEGE    B738 125005 125116  20   5 RYR31DH 160416 160416 2517.250  166.8333 2514.050  165.6333  195812034 3.322209
```

⇩

```
             fl_id  plan   id1   id2               time1               time2 FL1 FL2 stat        dist
      1:  195615342 FALSE  RJBB AGAVO 2016-04-11 13:06:00 2016-04-11 15:41:28   0 340    0  571.017106
      2:  195615342 FALSE AGAVO DONVO 2016-04-11 15:41:28 2016-04-11 15:46:36 340 341    0   39.657760
      3:  195615342 FALSE DONVO  *KM1 2016-04-11 15:46:36 2016-04-11 16:38:12 341 341    2  402.881043
      4:  195615342 FALSE  *KM1 IDROS 2016-04-11 16:38:12 2016-04-11 21:28:33 341 380    0 2350.302282
      5:  195615342 FALSE IDROS MASAV 2016-04-11 21:28:33 2016-04-11 22:02:33 380 400    0  261.638644
     ---
2139082: 1501276103 FALSE  EGGW   BKY 2016-04-12 23:40:00 2016-04-12 23:44:15   5  30    0   17.349463
2139083: 1501276103 FALSE   BKY BUSTA 2016-04-12 23:44:15 2016-04-12 23:45:48  30  40    0    6.187096
2139084: 1501276103 FALSE BUSTA LOREL 2016-04-12 23:45:48 2016-04-12 23:47:17  40  39    1    6.495301
2139085: 1501276103 FALSE LOREL  EGSS 2016-04-12 23:47:17 2016-04-12 23:51:05  39   3    1   13.155447
2139086: 1501276104 FALSE  ENKR  ENSS 2016-04-13 09:22:00 2016-04-13 09:36:36   3   0    1   44.630845
```

*Figure 1. Data processing of the Raw Data Filter script*

## Flight separation calculator

The functionality of this script is to discretize flight trajectories temporarily with a given timestep and, then, calculate separation conflicts between all the discretized trajectories. In order to do that, flight separation minima are provided as an input, as well as the filtered route data obtained from the previous script.

First of all, the route data is discretized, in a parallel loop, interpolating linearly the trajectory of each flight within the values of a time vector created previously with the timespan and the time values when route data need to be interpolated.

Then, a filtering process based on position is made, first, filtering points inside a square with given coordinates and, then, applying pointinpoly function using the boundary points of the Spanish FIRs, as explained in the report.

Finally, another parallel loop is done, analyzing for each time value discretized all the flights present over Spain, that is, all the flights that can enter in conflict between them and creating a combination table where all of them are classified by time.

Then, a first approximate vertical and horizontal flights with a computationally simple calculation is obtained for each pair of flights in the combination table to discard pairs clearly distant and exclude them from the combination table.

Finally, the remaining flights are deeply analyzed, obtaining the horizontal and vertical distances among them with the distGeo function from the package Geosphere, made for calculating distances between geographical points analytically.

The flights that are below the minima values (both, horizontal and vertical minima) are kept as conflicts with the separation calculated for each timestep included in the data, which constitute the final output of the file.

## FRA simulator

The functionality of this script is, from all the interpolated flight data obtained in the previous script (before filtering the data geographically), detect Entry and Exit Points in Spanish FIRs among flight trajectories and keep them, to create straight trajectories and discretize them on time to finally, calculate conflicts as it has been done before for real flight discretized trajectories.

The first step of the script is to detect when a flight is entering or leaving a Spanish FIR. For this purpose, a parallel loop iterating over each flight is done, checking when there is a change in the FIR within the trajectory (after having classified each point in the real trajectory by FIR with pointinpoly) and storing these points with an in_out marker.

This marker is also used to highlight points within a FIR where a flight crosses the minimum Enroute flight level, as they are entering or leaving the airspace of analysis.

After having entry and exit points for each flight, linear trajectories are calculated between them, not considering now any previous navpoint that the real flight route followed. The trajectory time discretization is calculated among the starting and the final point as it has been done in the previous script.

Finally, conflicts occurred in the FRA computed trajectories are calculated also in the same way as it has been done previously.

The final output of this file is the route data of the FRA trajectories and the dataset of conflicts detected among flights.

## Results and graphs

The last script takes as inputs all the outputs from the previous scripts and is used only for representation purposes, making simple calculations if necessary, to compute the desired data for each figure needed for the key parameters presented in the report.

In this script, it is remarkable the use of ggplot2 package, the dygraphs package and the use of rworldmap package to obtain high resolution world maps to represent the geographical data.

For convenience reasons, this script is duplicated and non-FRA and FRA results are taken from each of the scripts separately.

# Appendix C: Analysis of planned flights data

In this appendix, the planned flight data corresponding to the same time period indicated in *4.1.3 Date of the analysis* of the main report with the same specific simulation parameters than the ones in the section *4.1.5 Specific simulation parameters*, the results are presented in several figures, representing the relevant parameters listed in the section in *4.1.4. Relevant parameters* of the main report.

The complete explanations of all the results, as it has been done in the main report is included here, making the lecture of the results presented here independent from the ones present in the main report.

## Safety analysis results

### <u>Current scenario</u>

#### Airspace load factor

The first indicator to consider is the airspace occupation and the EnRoute operations occurring in each moment in the Spanish FIR units.

The following profile represents the real-time air operations in each FIR and the total number in all the Spanish airspace.

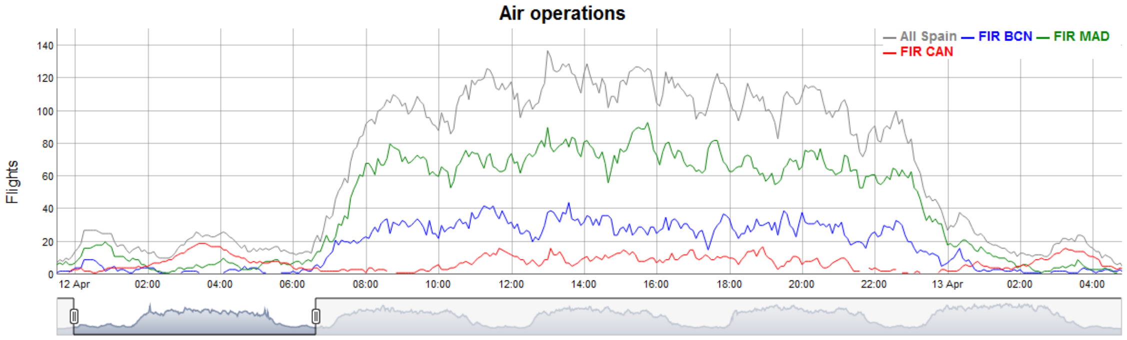


*Figure 2. Air operations above Spanish airspace in real time*

Considering this graph, it can be seen that a similar behavior in air operations takes place in each day of analysis, having between 100 and 120 flights in route over Spain in the period from 6AM to 10PM every day. In gross terms, the occupation of each FIR unit within this time period is fairly constant, with around 70 flights constantly over Madrid FIR, around 30 flights within Barcelona FIR and 10 flights in Canarias FIR.

The time period selected does not reflect any seasonality, as there is not any festivity within it and is selected far from vacation periods.

Considering FIRs individually and the hourly operations supported by them, the airspace load factor profiles are obtained. There is also the maximum airspace capacity available represented, taking as a reference the values presented in *Table 7* of the main report. As these values correspond to the configuration with maximum sectors active, which is not realistic for April and also need to be corrected from 2018 values to 2016 ones, that are more restrictive according to the expert opinion of an active ATCO consulted.

Then, the assumption made for available capacities consist in assume the 80% of the maximum values provided for 2018, taking in consideration that each FIR could have been operating with different sectors open and, consequently, with different % of the maximum capacity of the FIR.

In order to precise the exact maximum capacities present each day of the period analyzed, specific DDR2 data and the use of R-NEST software is needed to check the corresponding registers of Air Traffic Flow and Capacity Management (ATFCM).

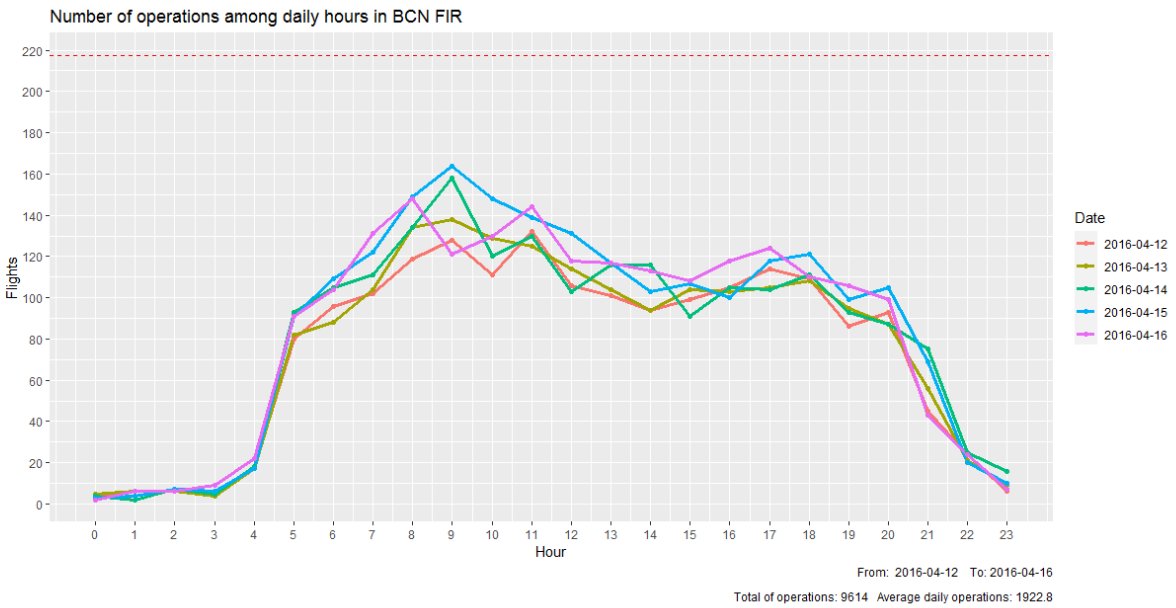


*Figure 3. Hourly flight operations in FIR Barcelona*

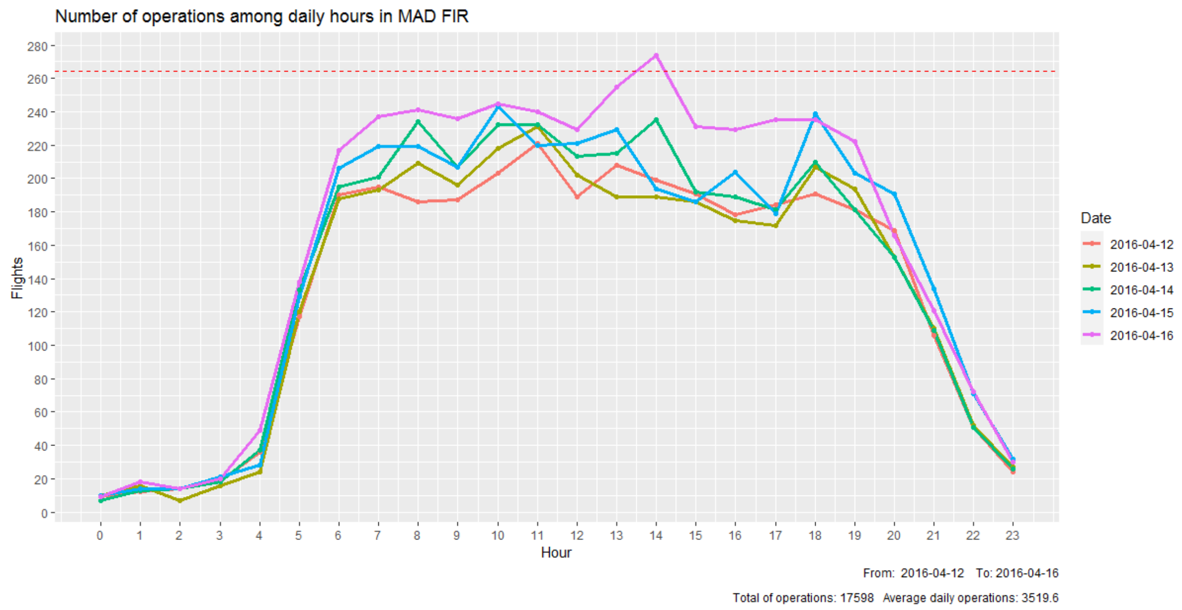


*Figure 4. Hourly flight operations in FIR Madrid*

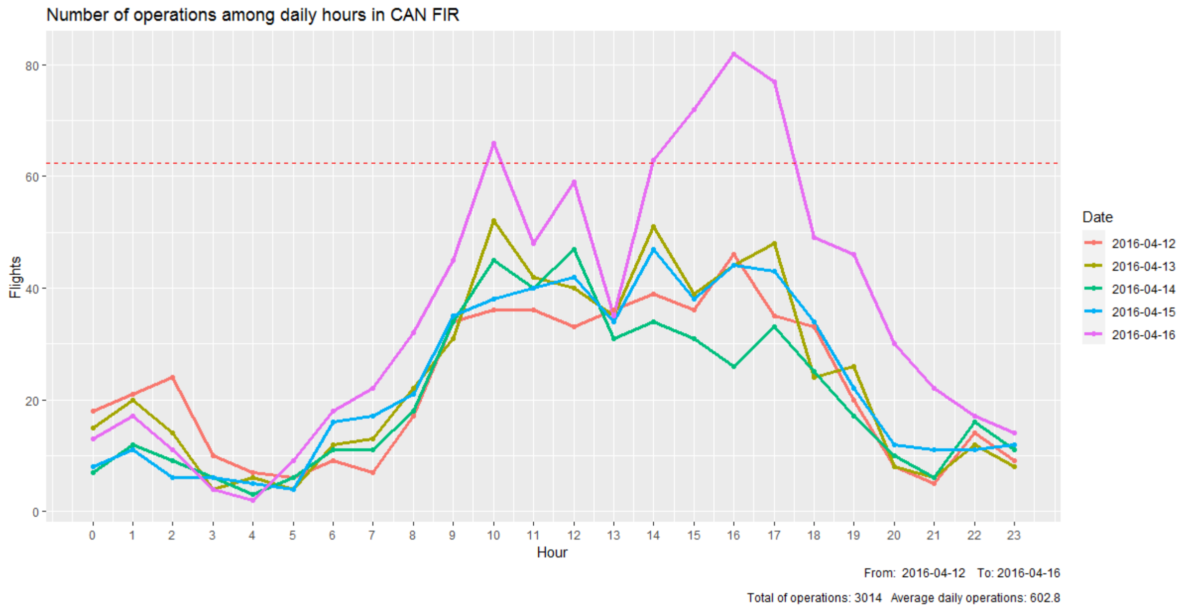


*Figure 5. Hourly flight operations in Canarias FIR*

Barcelona and Madrid FIRs show a stable behavior, being the hourly operations profile similar between the different days and far below the maximum capacity of the airspace for Barcelona and near the maximum capacity of the airspace in the case of Madrid, according to the values presented in the aforementioned table of the main report.

Canarias FIR, despite it presents a pretty stable profile in the working days of the week, a notable increase in operations is observed in Saturday 16th. This fact means that flights in Canarias FIR are more prone to suffer from seasonality and, consequently, the maximum capacity of the airspace is more likely to be overpassed, generating a situation where flight delays and separation losses occur more often.

### Overall occurrence of separation losses

Aiming to characterize the incidence of flight separation losses within the air movements taking place in Spain, the number of air conflicts has been represented in form of a daily profile, as shown below:

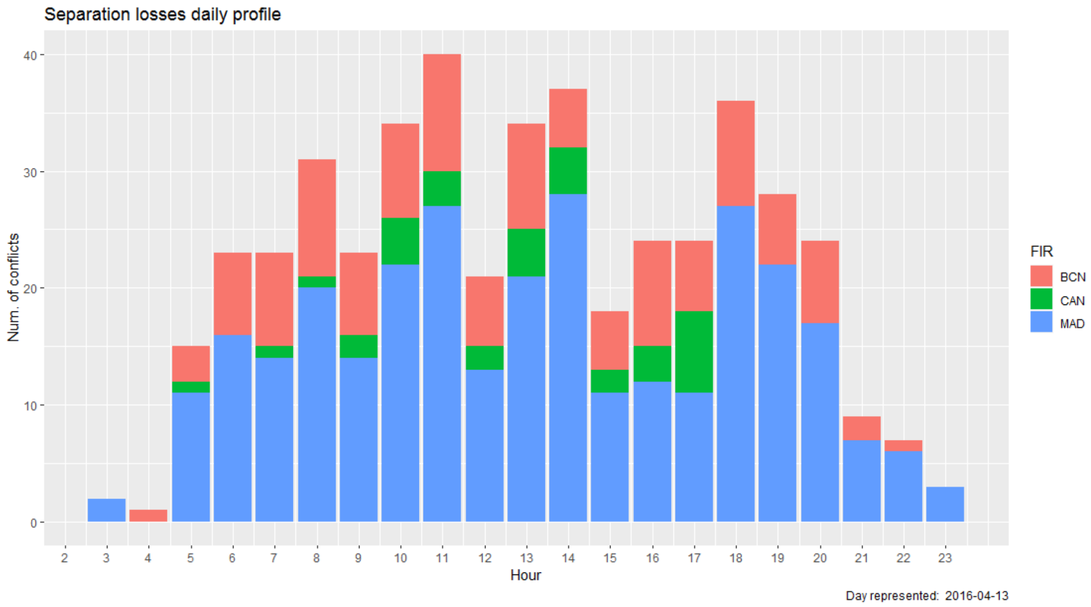


*Figure 6. Separation losses daily profile (working day)*

As expected, a direct correlation between the airspace load for each hour and the number of flight conflicts detected at the same time can be observed, especially for the case of Madrid, where the maximum loads -and consequently the most conflictive periods- are located in central daily hours. A pretty conflictive period can be observed too in Canarias during the afternoon, but this correlation is not as clear as it is Madrid for this case.

It's worthy to remind that, despite no ARES or disruptions are considered in the analysis, the flight data -which reflects the real trajectories flown- can be affected by this kind of events, so a wider analysis would need to consider the affectations of SUAs on the analyzed flight trajectories.

The results of the same analysis are represented by a weekend day from the same week.

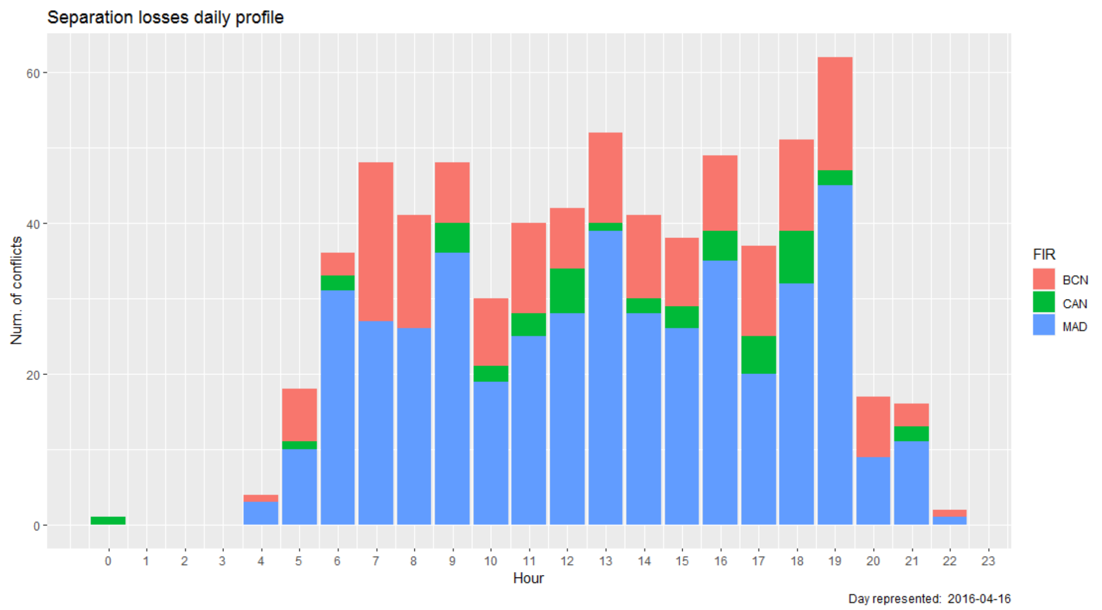


*Figure 7. Separation losses daily profile (weekend day)*

It can be observed that the overall amount of conflicts increases in the weekend, despite that the number of operations does not increase in the same proportion, at least in the major FIRs: BCN and MAD. Also, the conflicts' profile is more concentrated in the central daily hours, observing major number of incidences there, but a minor number of them in the hours at the edges of the graph.

It is noticeable that despite there is a sudden increase of operations in Canarias FIR from 3PM, there is not a direct impact reflected in conflicts occurred.

**Incidence of separation conflicts among daily hours**

In order to determine the incidence of separation conflicts in temporal terms, two indicators are considered.

The first one, represented in the following figure, is the total number of conflicts detected during the whole period of analysis classified by the hour in which they have taken place.

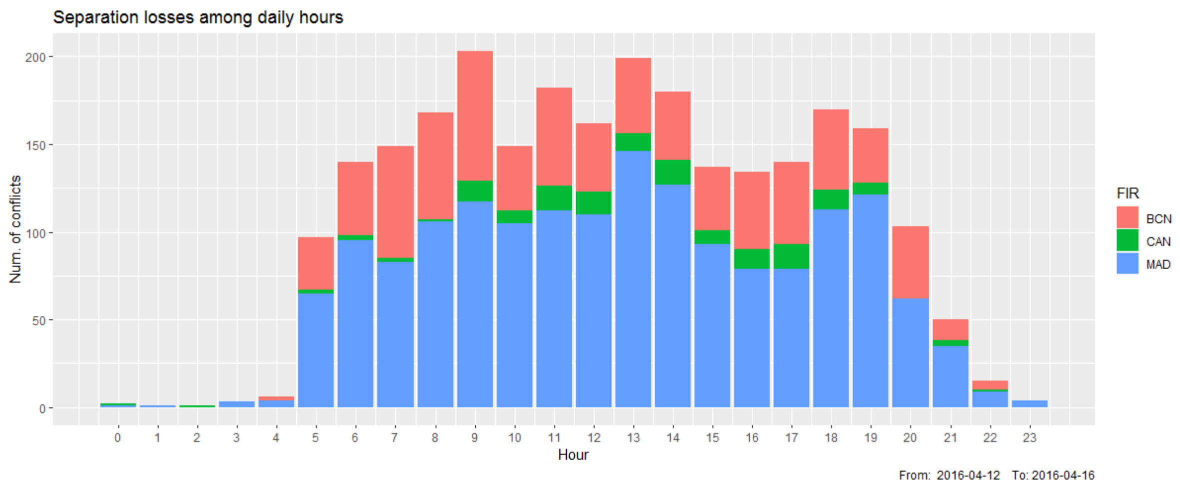


*Figure 8. Total separation losses by hour*

The most complex hours during the week analyzed can be identified -despite Figure 6 and Figure 7- does not account for each day specificities- and constitute a first approach in order to apply a time limited FRA.

In the following figures, the same indicator has been represented in relative terms, to better illustrate the impact of each hour in the daily balance of conflicts occurred.

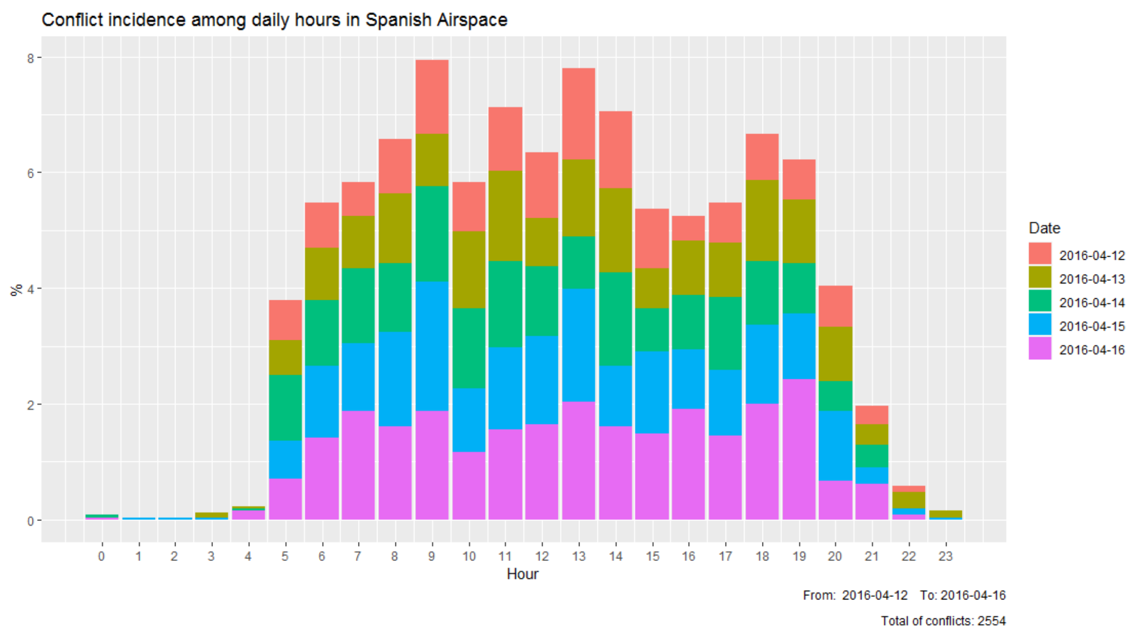


*Figure 9. Conflict incidence among daily hours in Spanish airspace*

From this graph, it can be seen that more than 40% of the conflicts during the analyzed week occurred in the six hours between 9AM and 2PM -both included-.

Obviously, the conflict incidence during the daily hours vary from one FIR to another and mitigation measures should be taken individually. For this reason, independent profiles of relative incidence of conflicts among daily hours are also obtained and taken in consideration:

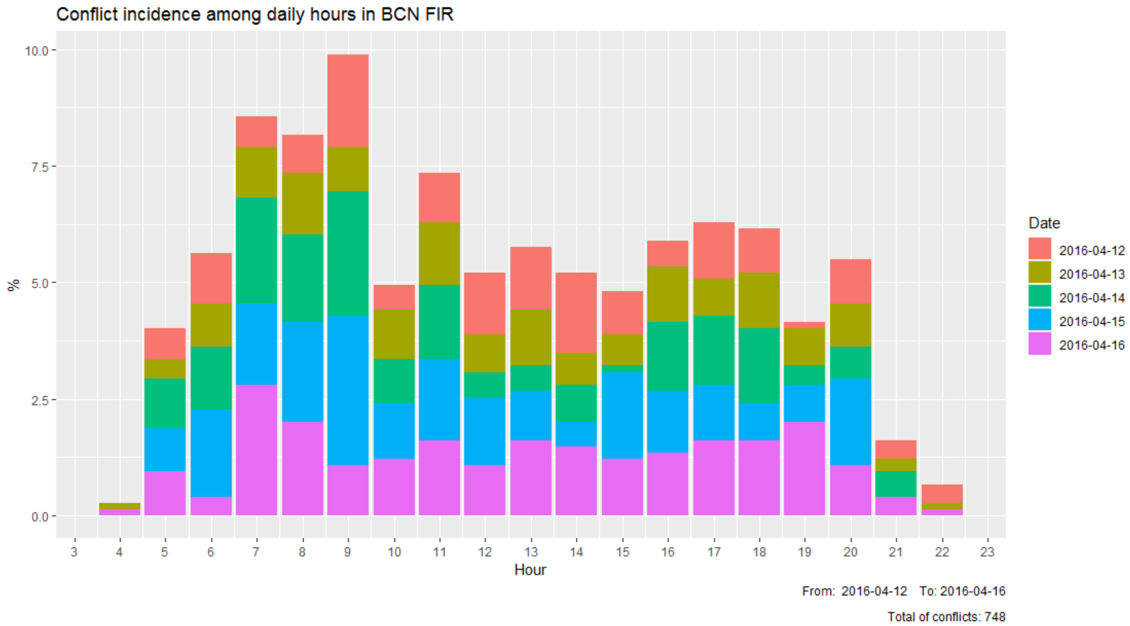


*Figure 10. Conflict incidence among daily hours in BCN FIR*

In Barcelona FIR, there is more concentration of conflicts in the early morning than in other daily hours, being from 7AM to 9AM -inclusive- the timespan with around 25% of the weekly separation losses.

Also, Barcelona accounted for a total of 748 conflicts, representing the 29.3% of the total Spanish conflicts detected (2554, according to Figure 9).

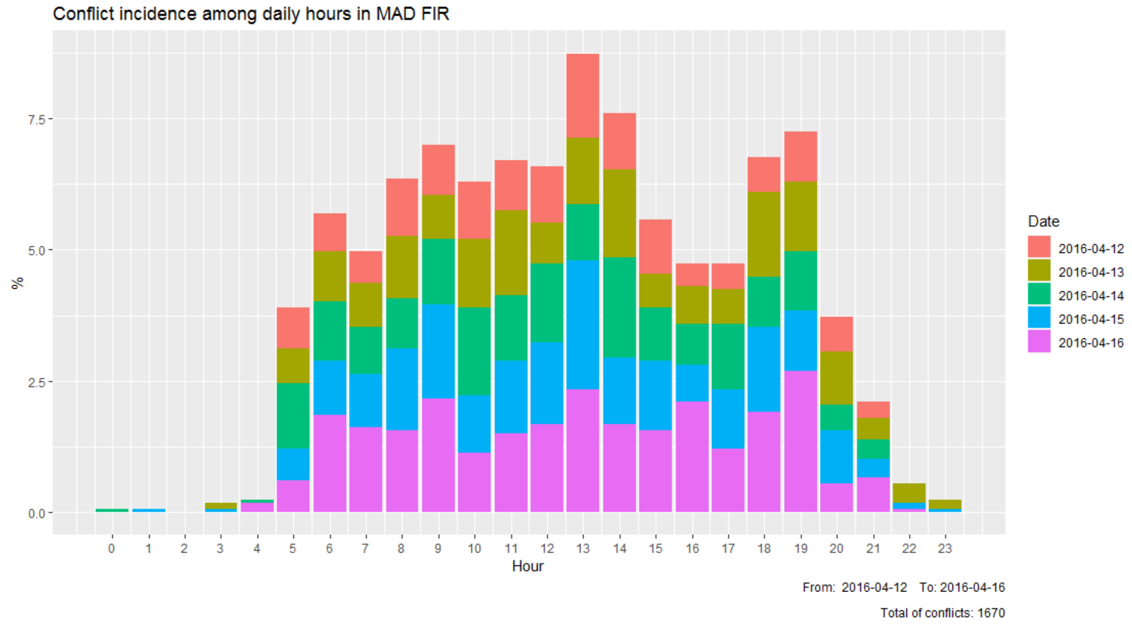


*Figure 11. Conflict incidence among daily hours in MAD FIR*

On the other hand, Madrid has a fairly regular presence of conflicts along the day, with higher incidence in the morning hours its peak in central daily hours (1PM and 2PM). As the most concurred airspace in Spain, Madrid FIR present the higher amount of conflicts, 1670, representing the 65.4% of the total.

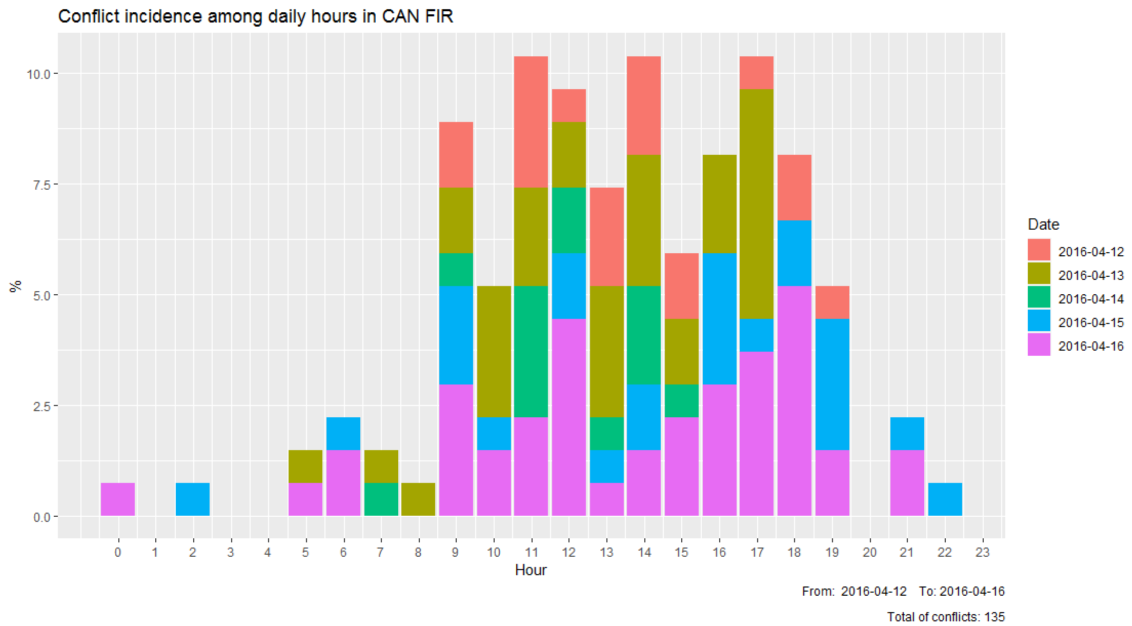


*Figure 12. Conflict incidence among daily hours in CAN FIR*

Finally, Canarias has an irregular conflict distribution, presenting oscillations between 5 and 10% of the weekly conflict's incidence from 9AM to 7PM, being unclear to determine target hours to apply mitigation measures, such as time-limited FRA or similar.

In the whole of Spain, the 135 conflicts in Canarias represent the 5.3%, a low percentage explained by its relatively low number of flight operations.

### Density of conflicts among daily hours

Through this indicator, the relative amount of flights in conflict is accounted, considering the total traffic present in the airspace at the same time -airspace load factor data-.

It has to be taken into account that, as the total traffic is relatively low during night hours, a single separation loss accounts significatively. This fact explains the peaks observed in all the graphs from 0 to 6h. But that does not mean that the conflicts occurred during the night period should be ignored, as with a less concurred airspace, a better flight distribution and performance -in terms of safety- of the Free Routing may be expected.

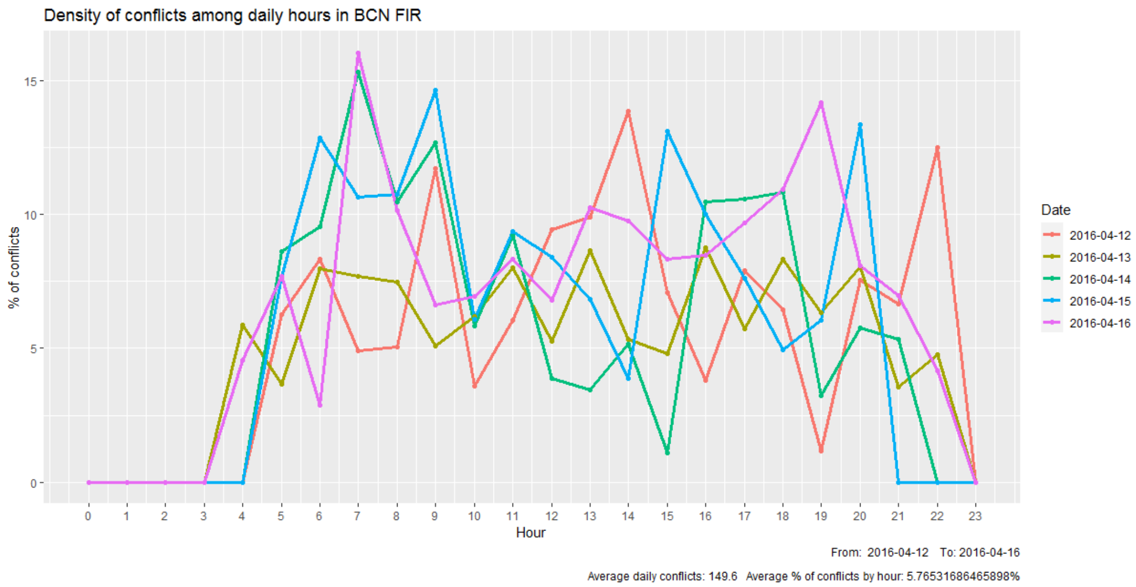


*Figure 13. Density of conflicts among daily hours in BCN FIR*

In the case of Barcelona, it can be seen that during daily hours, the percentage of conflicts varies between 5 and 15% among the total number of flights, being the mean in 5.8%. As commented before, the fluctuations on the percentage are caused by the number of flights, which can be reduced in some hours.

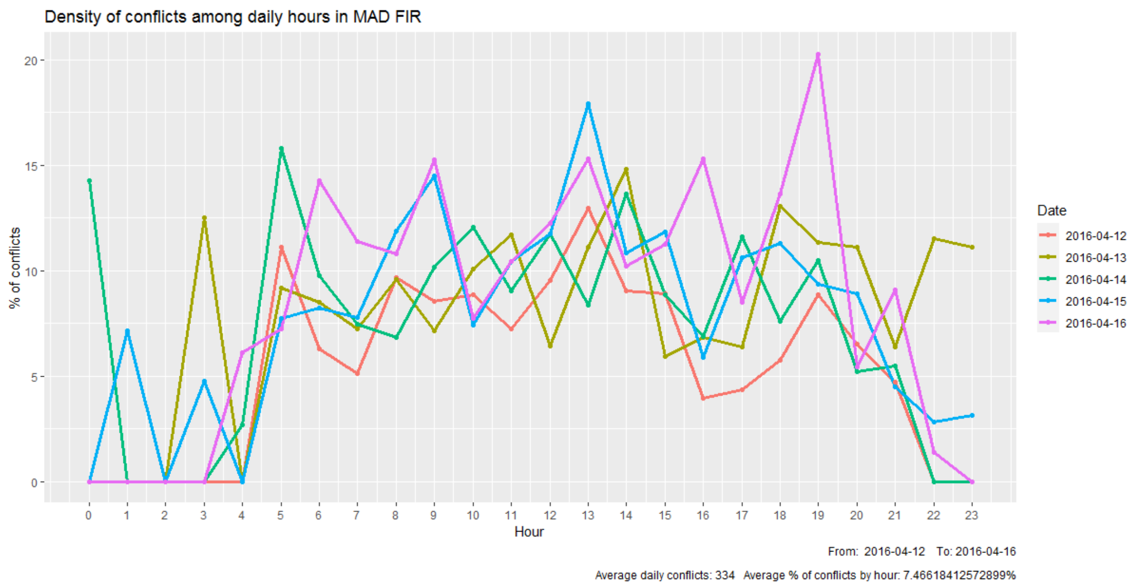


*Figure 14. Density of conflicts among daily hours in MAD FIR*

Although Madrid presents less fluctuations compared with Barcelona, the hourly percentages of conflicts are higher -the mean is 7.5%-, having a peak on Saturday at 7PM, reflected in Figure 7 but not as an overload or a peak in operations, as shown in Figure 4.

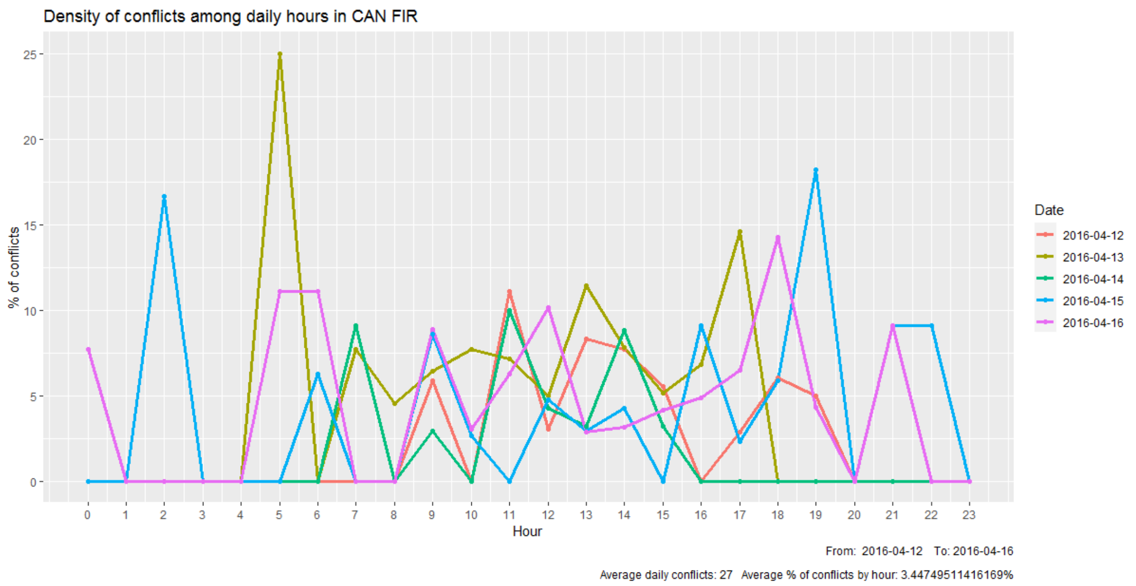


*Figure 15. Density of conflicts among daily hours in CAN FIR*

Finally, Canarias present a highly unstable percentage of flights in conflict due to the low number of operations present in its EnRoute airspace. Despite that, the mean density of conflicts is much lower than Barcelona and Madrid with a value of 3.4%, as there are several hours without any occurrence of conflicts.

### Geographic distribution of the conflicts observed

In order to characterize the geographical distribution of the conflicts and detect the areas within each FIR more susceptible to present flight convergences, the conflicts registered are represented on the map.

As the aim of this figures is to have a quick shot of the conflict locations, all conflicts in each FIR are represented, what can generate a bit of confusion due to the elevate number of conflicts occurred.

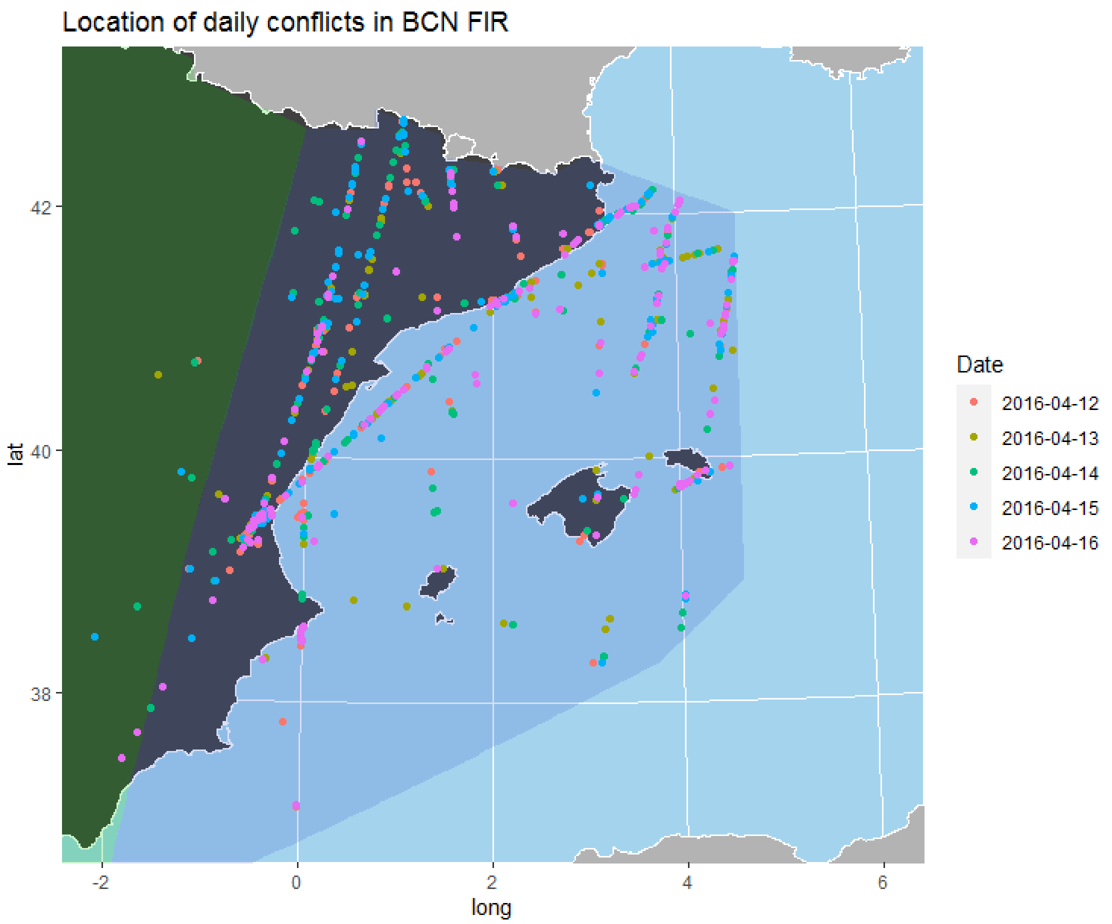


*Figure 16. Location of daily conflicts by date in BCN FIR*

But what is found and is interesting to observe is that most of the conflicts occur in positions that, superposed, are located forming lines. This fact is easily explained by the existence of the Air-Routes and its use in navigation by waypoints, situation present in the current scenario.

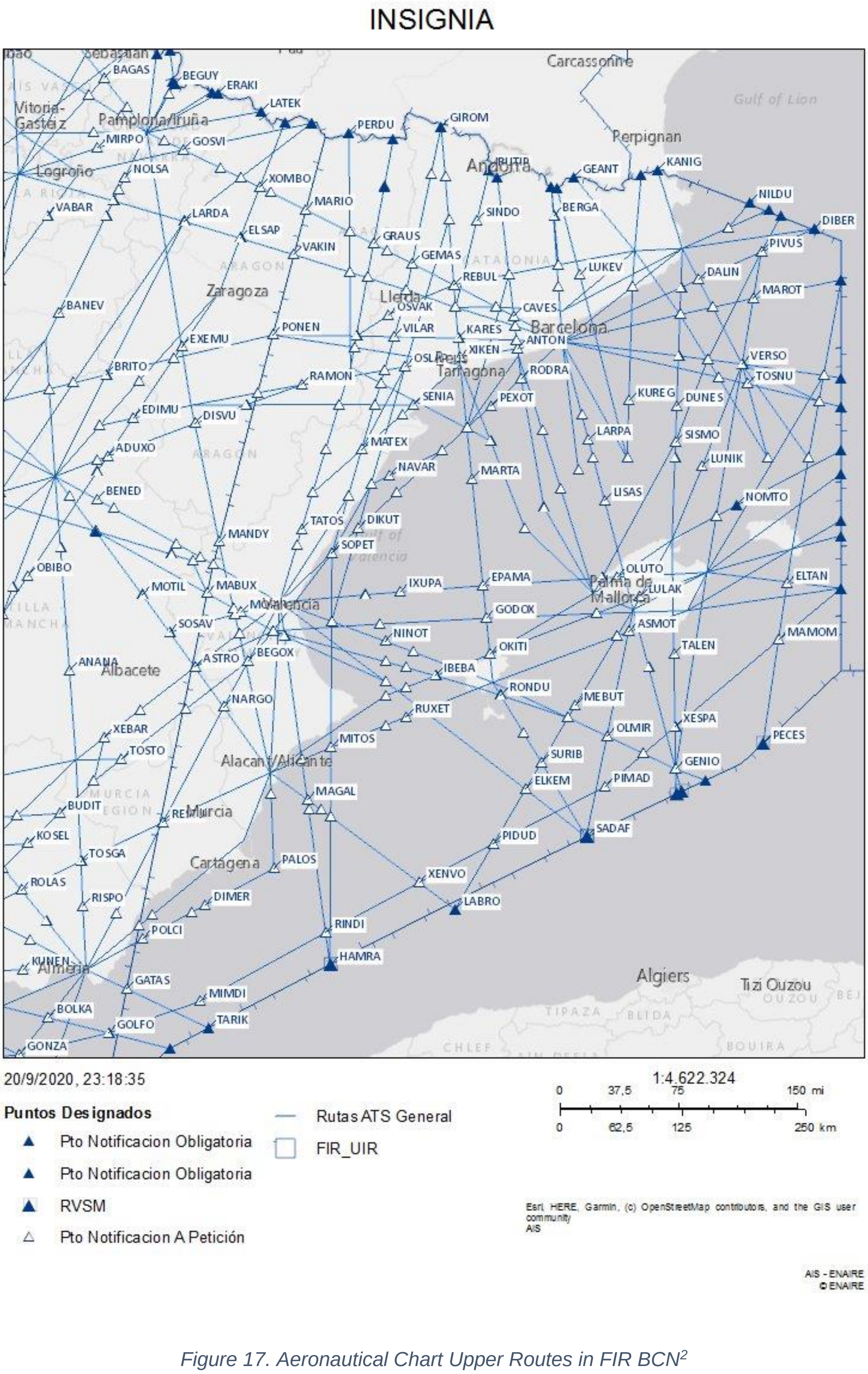


*Figure 17. Aeronautical Chart Upper Routes in FIR BCN[2]*

[2] Source: AIP Spain (INSIGNIA charts published by ENAIRE)

It is also worthy to mention that some conflicts in points out of the Barcelona FIR -as an example- are registered and represented. This happens because, for each conflict, the most critical point (so, the closest point between aircraft involved) is kept as a reference and the conflict is located there, specifically in the mean point between the aircraft location.

Otherwise, the computation of the conflict in terms of FIRs considers the starting point, so the point where the conflict is originated and notified to the corresponding ATC unit.

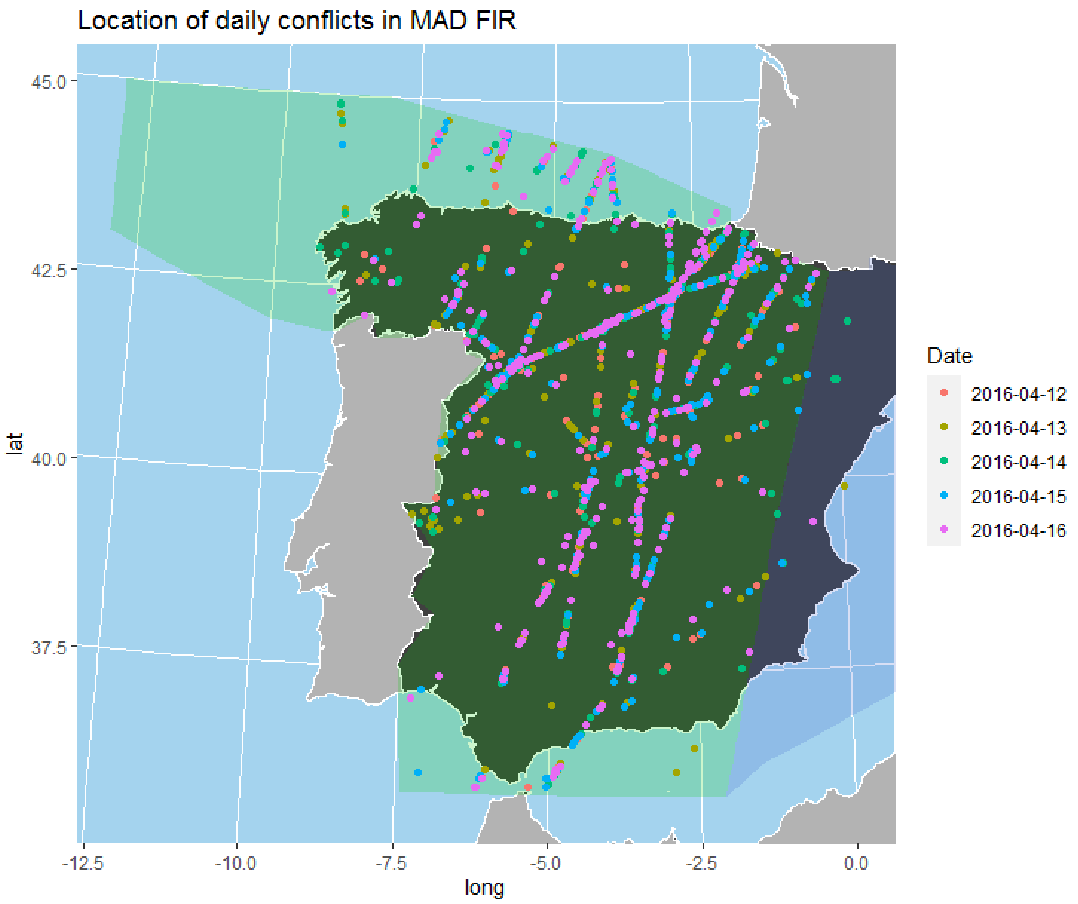


*Figure 18. Location of daily conflicts by date in MAD FIR*

The same tendency pointed by the case of Barcelona can be observed in Madrid, being the majority of the conflicts over lines, corresponding with the Upper Air Routes present in Madrid FIR. It is also noticeable the relatively high presence of conflicts in the North-Centre of the FIR, probably because of the proximity of the French Brest FIR. Several spread conflicts can be also found in the vicinities of Portuguese Lisbon FIR.

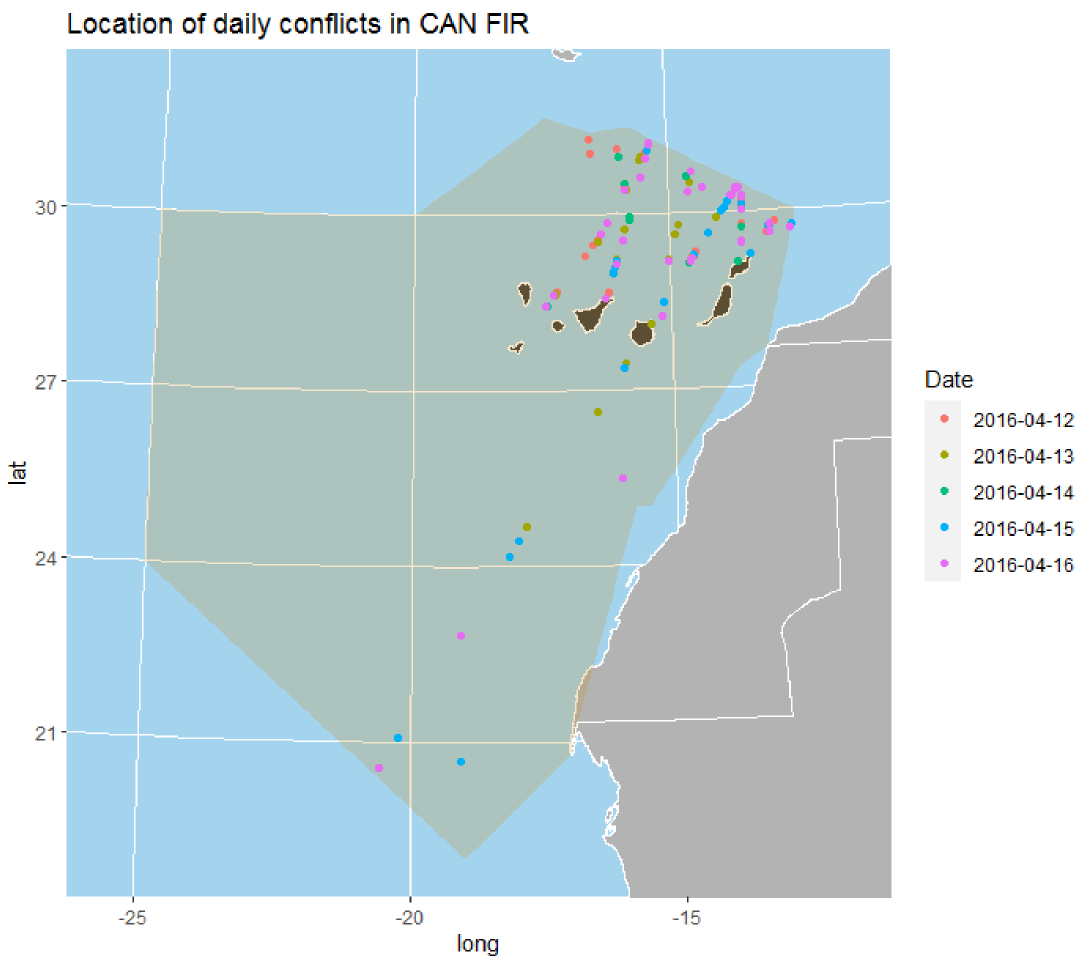


*Figure 19. Location of daily conflicts by date in CAN FIR*

Finally, in the case of Canarias, it can be seen that most of conflicts are registered in the North-East. This occurs because most of the flights passing by start or end at the islands and connect with Europe. Currently it is not usual to pass through Canarias airspace in transoceanic flights, as there is not yet any concurred direct flight corridor between Europe and South America.

**Severity of the conflicts distributed among daily hours and geography**

In order to measure quantitatively the severity of a flight separation conflict, an indicator has been developed, which accounts for the inverse of the separation between the flights involved and the timespan during which the conflict persisted. The indicator is computed according to the following expression:

$$S = \left(\frac{D_{\max} - D_{min,conf}}{D_{max}}\right)^2 * (100 + 10 * T_{factor})$$

Where,

- S accounts for **severity** and goes from 1 (minimum) to infinite (maximum)
- $D_{max}$ is the maximum distance possible between flights in a conflict (total distance considering the separation equal to the minima values[3], 9260 m)
- $D_{min,\ conf}$ accounts for the minimum separation between flights involved in a conflict (absolute distance)
- $T_{factor}$ considers the duration of the conflict having a value equal to the duration of the conflict in blocks of 5 minutes -the value in minutes of the time discretization-. E.g: 5 min or less are a $T_{factor}$ of 1, while 15 min or less are a $T_{factor}$ of 3.

It can be seen that this indicator can adopt a value that goes from 0 to 1 by means of the separation distance. This value is squared, so the output of this factor grows exponentially with smaller $D_{min}$ . This factor is right after multiplied by 100 for scaling purposes, as a scale from 0 to 100 it's better understandable and readable in a graph. Finally, the timespan of the conflict is considered as an additive term in the scaling value -in tenth, to not be under or over valued in the final severity value-.

To better illustrate the calculation of the severity value, an example is shown:

In the first day of analysis, the 12th of April, a conflict is reported within FIR Madrid at 9:05AM between two aircraft. The first flight involved is a Boeing 772 of AeroMexico flying from Mexico City International Airport to Madrid-Barajas Airport. The second one is an Airbus A333 of Delta Airlines flying from Madrid-Barajas to John F. Kennedy International Airport.

The conflict happened over Santiago de Compostela area, in Galicia region, being the aircraft flying at FL 388.9 and FL 370, respectively.

The conflict lasted 5 min -or less-, so there is only 1 appearance of the conflict in the output, according to the time discretization adopted. The minimum separation registered between the two flights in this conflict has been 1891ft vertically and 0.578 NM horizontally, what means a total of 1072 meters of absolute distance in the closest point.

Then, the calculation of the severity factor of this conflict is the following:

$$S = \left(\frac{D_{\max} - D_{min,conf}}{D_{max}}\right)^2 * (100 + 10 * T_{factor}) \rightarrow \left(\frac{9260 - 1072}{9260}\right)^2 * (100 + 10 * 1) = 86.05$$

This rationale is followed, as the real threat in terms of safety is the separation loss and, secondarily, the time that it lasts if the separation is high enough to clearly avoid an eventual mid-air collision.

[3] See *2.1.2 Separation standards* in the main report

Severity of the conflicts is analyzed from a dual perspective: chronologically, in order to identify the hours where conflicts are more susceptible to be severe; and geographically, identifying locations where conflicts occur with the worse conditions to keep the aircraft separated according to the safety standards.

For representation purposes, each conflict has been classified according to its severity value in a qualitative scale:

- Low severity conflict: [0 – 25]
- Medium severity conflict: (25-75]
- High severity conflict: (75-100]
- Very high severity conflict (100, inf)

By the means of this study, the values selected in this scale represent a qualitative approach based on the author criteria and the experience acquired through several samplings of flight data. A more detailed approach on flight conflicts severity assessment should be made specifically in further studies.

The daily hour profiles by each of the FIRs analyzed during the entire period considered are the ones which follow:

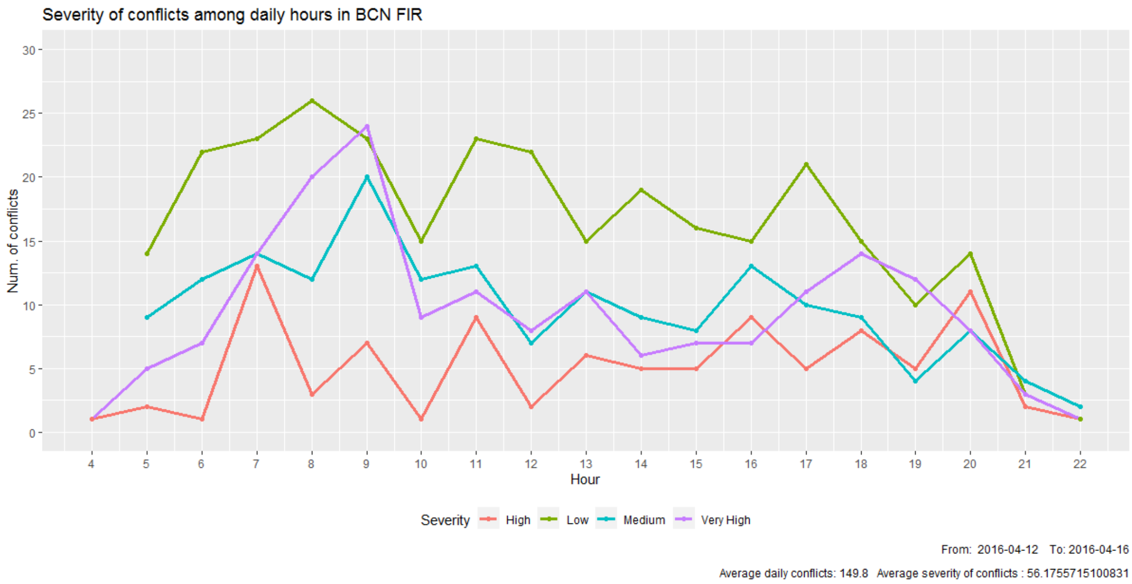


*Figure 20. Severity of conflicts among daily hours in BCN FIR*

From this profile taken in Barcelona, it can be seen that most of the conflicts belong to “Low” severity category, followed by “Medium” severity and “Very High” severity with similar numbers.

However, the quantity of very high severity conflicts from 7AM to 9AM is unexpectedly high, so more information on this point has been obtained and provided:

Most of the very high severity conflicts are reported in the 14th and 15th of April, are located in specific locations and, in some cases is a dual conflict where 3 different flights are involved. Conflictive locations are developed below.

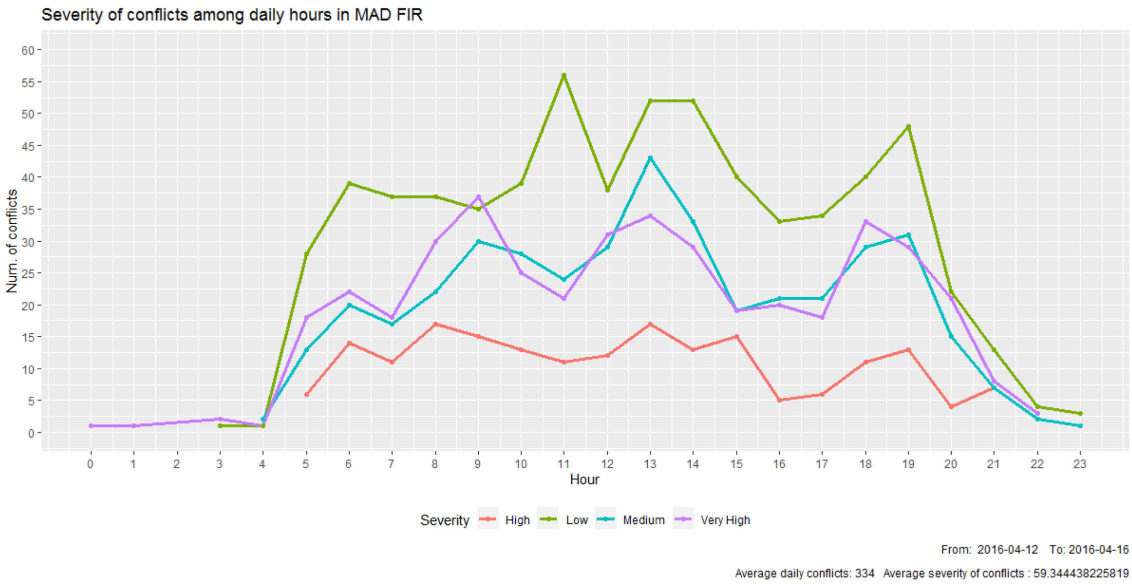


*Figure 21. Severity of conflicts among daily hours in MAD FIR*

In Madrid's conflicts, the tendency is the same observed in Barcelona, being Low severity conflicts, followed by Medium and Very High severity types with similar values. It can be observed also that increases and decreases in conflicts for each hour affect in similar proportions each category, registering increases in conflicts of almost all severities between 7AM and 9AM, between 12AM and 1PM and from 5PM to 7PM.

On the other hand, decreases can be seen across severities between 1PM and 3PM.

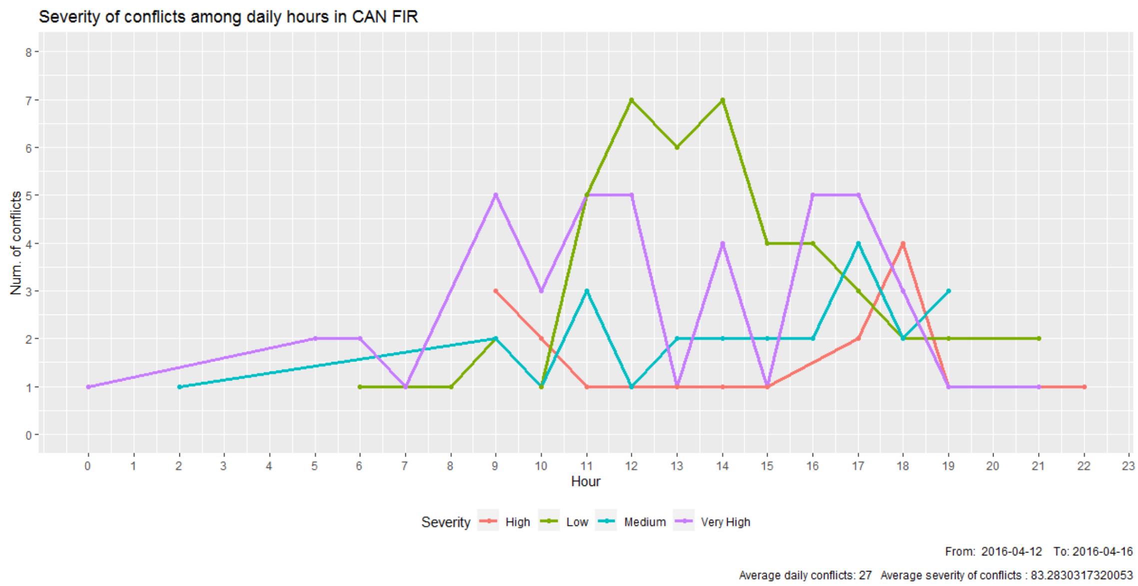


*Figure 22. Severity of conflicts among daily hours in CAN FIR*

In the case of Canarias FIR, most of the conflicts correspond to low and very high severity categories and the profile present acute changes due the low number of conflicts present. However, as happens in Barcelona, a deeper insight in very high severity profiles is needed, as they represent a very significant percentage of the total of conflicts.

Though that, any pattern is observed, being all the very high severity conflicts equally spread along the days analyzed and not located in specific places. A higher refinement in the temporal discretization in further stages could help to clarify the origin of some of these conflicts.

If conflicts are located on the map and colored according to its severity, we can observe some geographical patterns.

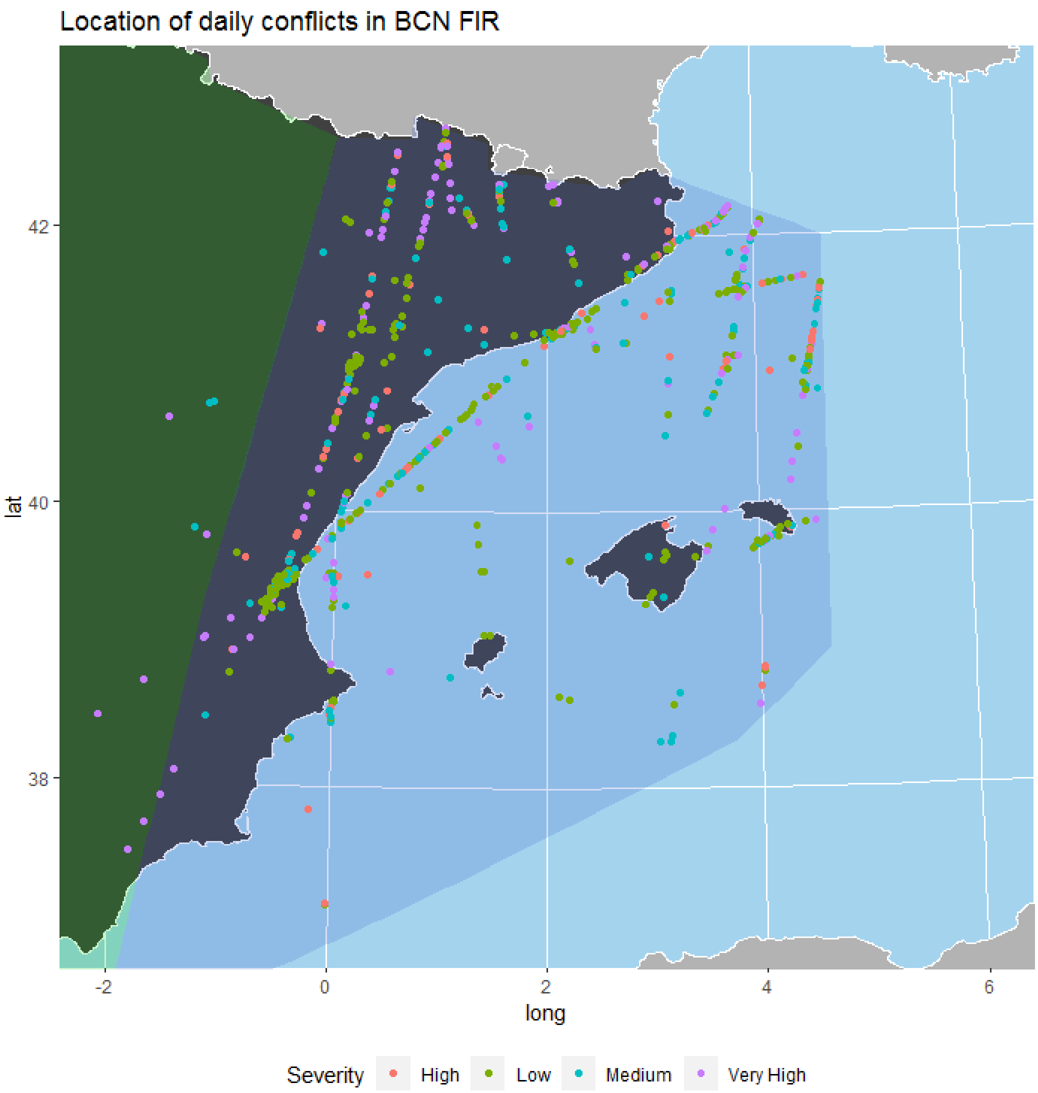


*Figure 23. Location of daily conflicts by severity in BCN FIR*

In the case of Barcelona, there is a notable concentration of low and medium severity conflicts over Valencia, where there is a connection node between several air routes, while there is an elevated concentration of very high conflicts in the north boundary of Barcelona FIR, specially in the region of Lleida and Vall d'Aran. This can be explained due to constraints in flight routes due to orography and because of the proximity of France, being a location where cross-country control procedures need to be applied.

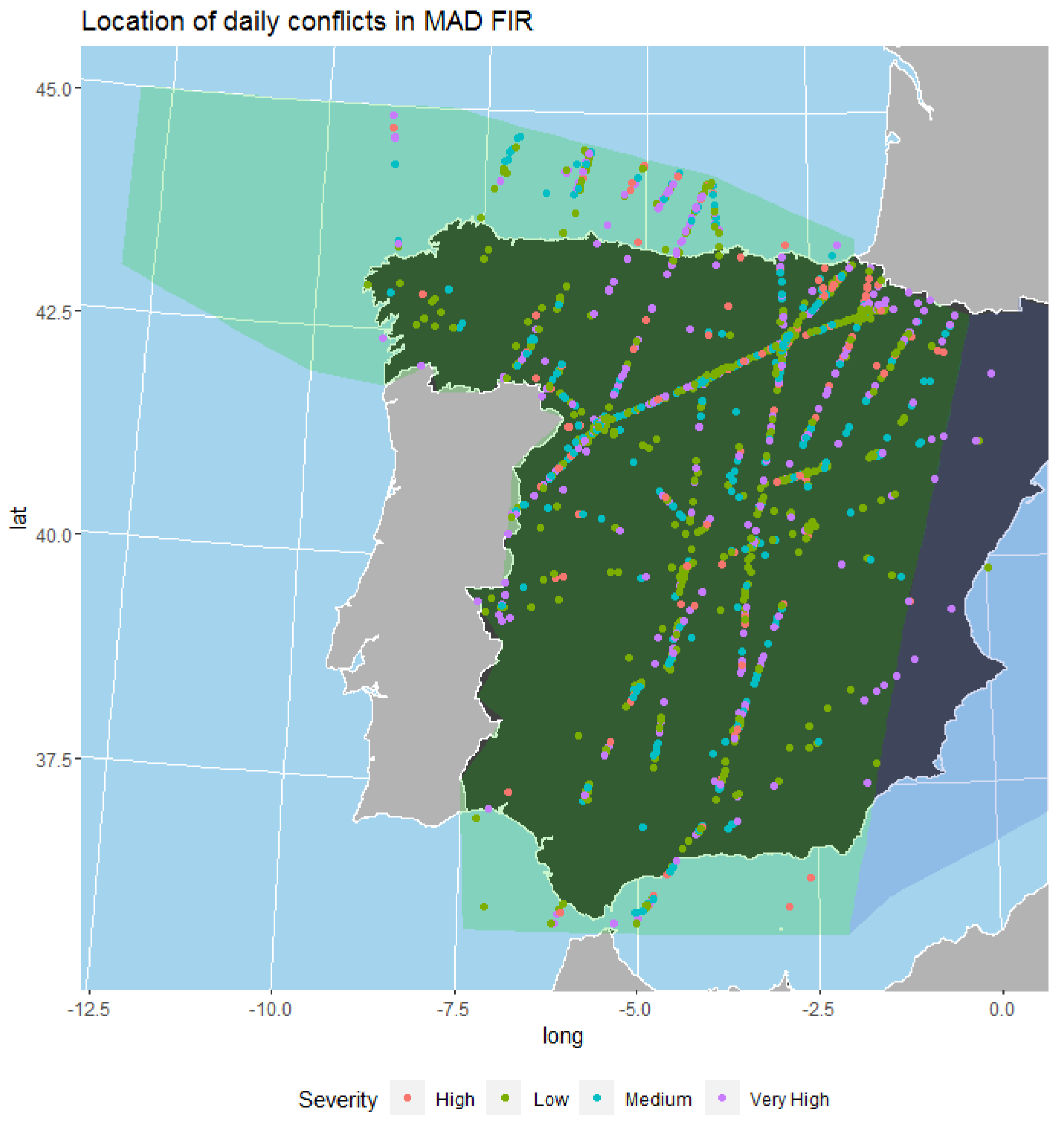


*Figure 24. Location of daily conflicts by severity in MAD FIR*

A similar situation happens in Madrid, where Very high severity conflicts are mostly located near Portugal and France borders and some of them in the boundary between Barcelona and Madrid FIRs. Apart of this observation, conflicts from all severities are located in equal proportions within the air routes present in Madrid FIR.

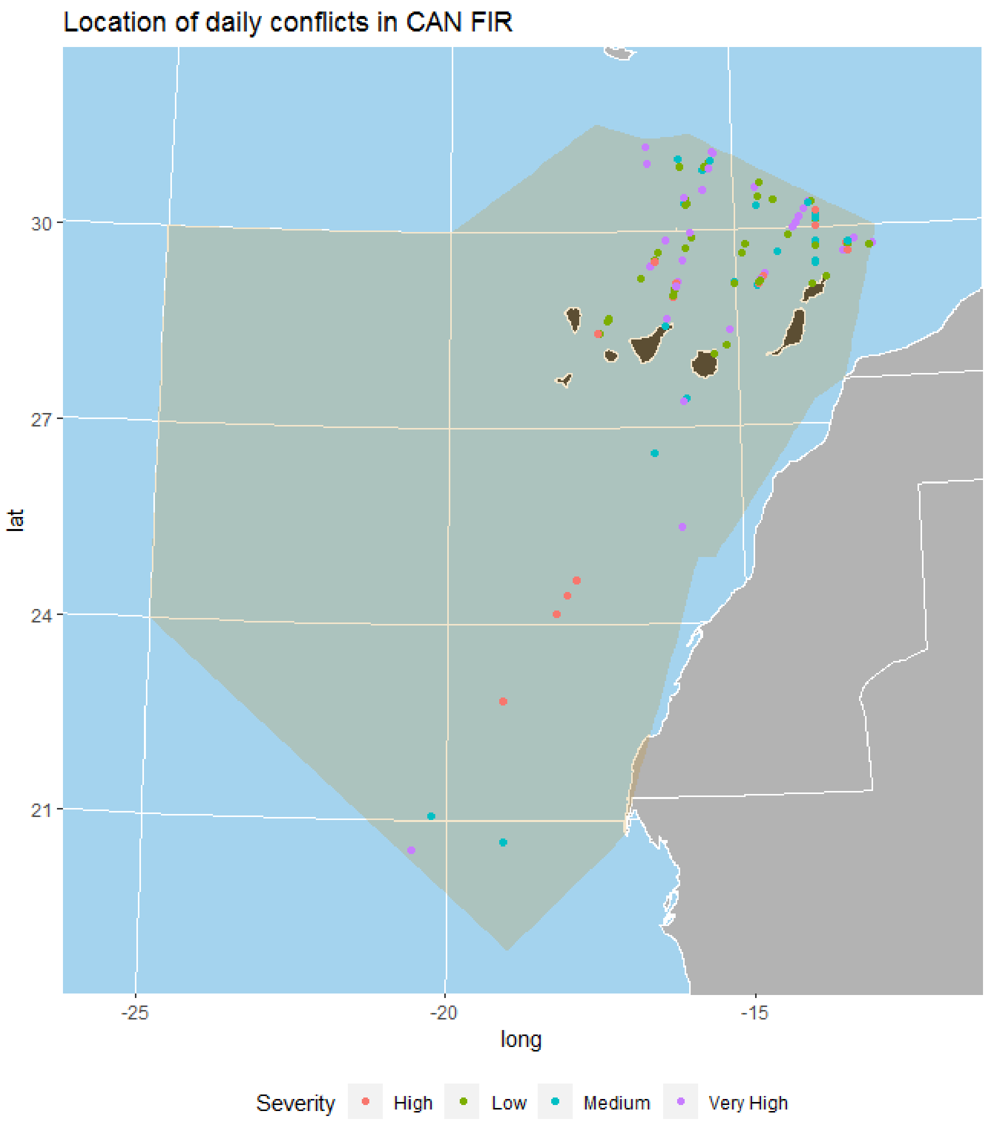


*Figure 25. Location of daily conflicts by severity in CAN FIR*

As it has been pointed previously, there is not a clear pattern of the conflicts occurred within the airspace, nor geographically. It is true that there is major incidence of Very high severity conflicts close to the Nort-East FIR boundary, being low severity conflicts more located over the islands.

But this phenomenon is not totally clear and need to be studied specifically trough a more refined and dedicated analysis, not performed in this preliminary stage of the FRA study.

## FRA Scenario

### Rationale of the design

In order to detail the rationale followed in the simulation of this scenario, the following example is created by means of this illustration:

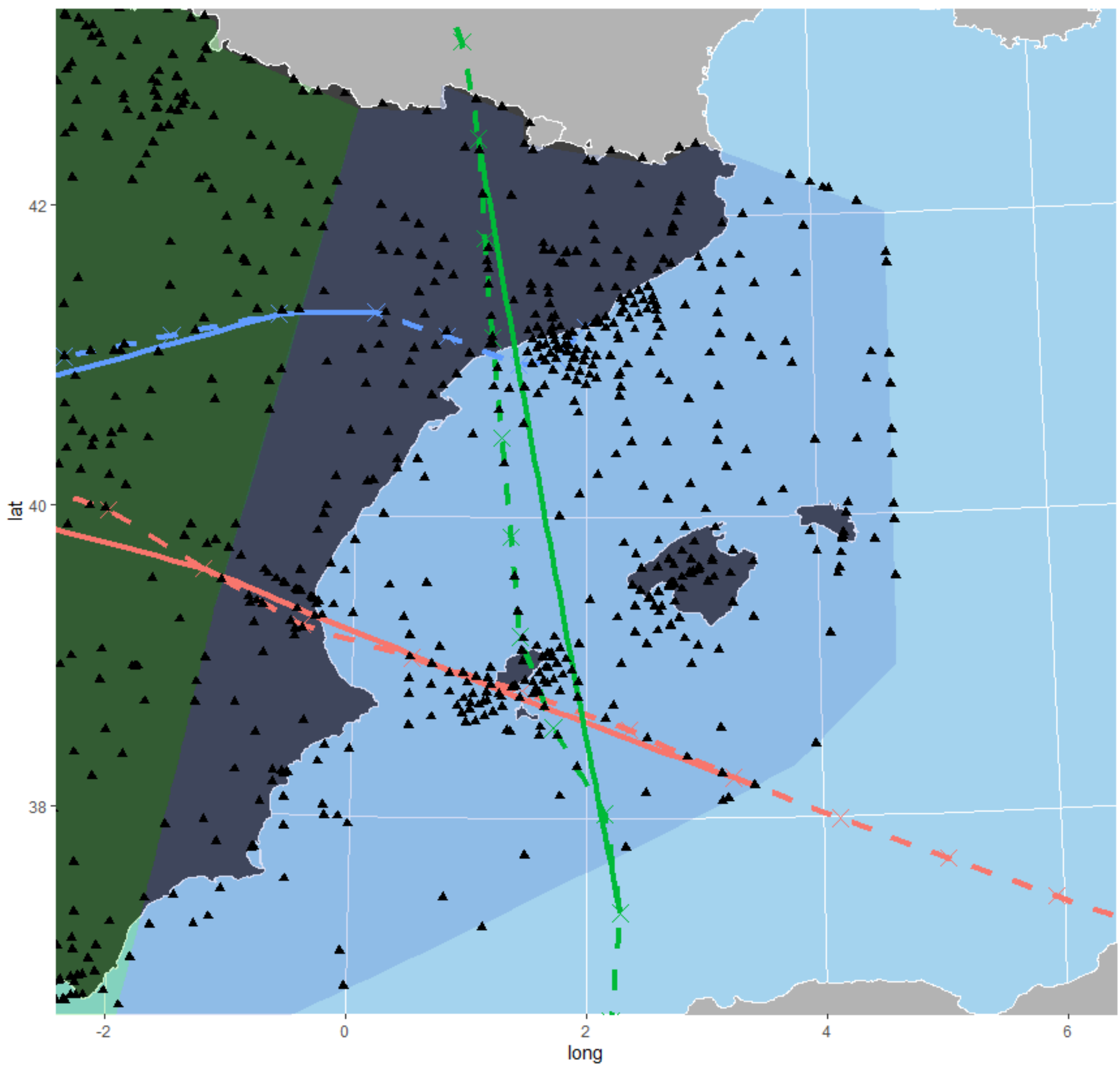


*Figure 26. Comparative scenario: point-to-point (dashed) vs free routing (continuous)*

The figure shows the trajectory of three random flights registered during the period of analysis in both scenarios simulated, navigation by waypoints (dashed line) and free routing (continuous line). As trajectories has been in both cases temporarily discretized, discretization points are represented in the figure with a cross symbol -in this case, only for routes navigation by waypoints-. Spanish waypoints have been included in the representation with black triangles, to better illustrate navigation by waypoints in the routes taken as reference.

In the FRA scenario, for each flight passing through an FRA unit (a FIR/UIR, according to the scenario simplifications) the boundary waypoints corresponding with the entry and the exit points of the flight with the current situation are kept. The most illustrative example of this in the previous figure is the green flight: the current trajectory (point to point) is the dashed line, from which the first point registered within BCN FIR has been kept as an Entry Point. To compute the free route trajectory of that flight, the first point after the flight left BCN FIR has been also taken as the Exit Point. The free route trajectory, then, is a straight trajectory between the Entry and the Exit points.

The same situation happens in the case of the red flight, but for this case, a new trajectory path is computed when the flight changes from BCN FIR to MAD FIR, being the first point within the new FIR an Entry Point and an Exit Point at the same time.

In the case that the flight enters or leaves the FRA in a point located within the FRA unit (by this analysis TMA is not considered as FRA), this point will be considered as the entry or the exit point. This situation occurs in the case of blue flight, which departed from Barcelona airport. The flight does not leave TMA until having passed the border between Catalonia and Aragon. There, the first registered point with flight altitude above FL245 is taken as an Entry Point.

### Airspace load factor

The airspace load factor in this scenario is practically equal as the scenario without considering an FRA (see Figure 3, Figure 4, Figure 5).

This occurs because the FRA trajectory computation is made using as Entry and Exit points the location (and the passing times) existing in the current scenario, having differences only in the occurred between the two points. By this reason, changes in FIR hourly occupations are not expected in an appreciable scale with respect to the scenario considered previously.

### Overall occurrence of separation losses among daily hours

As it has been done in the previous scenario, the number of air conflicts is represented as a daily profile for a working day and a weekend day, showing the total number of conflicts by hours and classified by FIR.

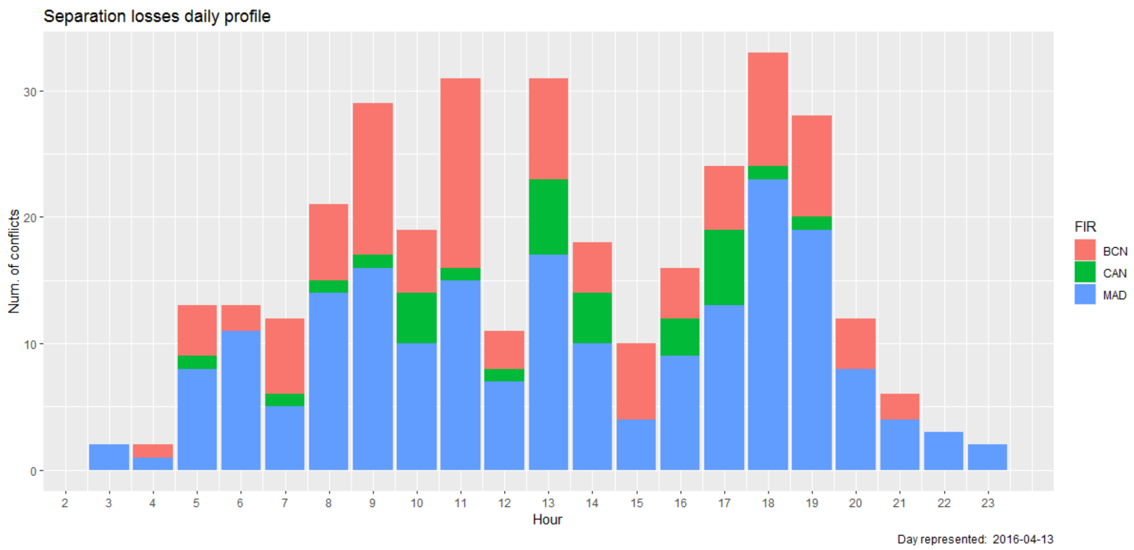


*Figure 27. Separation losses daily profile in FRA (working day)*

Compared with the non-FRA scenario, the gross number of conflicts has dropped slightly, especially in the early morning and in 12AM and 3 PM, hours that were already relatively low in conflicts in the previous scenario.

It can be seen, in comparison also with Figure 6, that Madrid FIR is the airspace where more conflicts reduction is achieved, while conflicts in Barcelona and Canarias raise slightly in the FRA scenario.

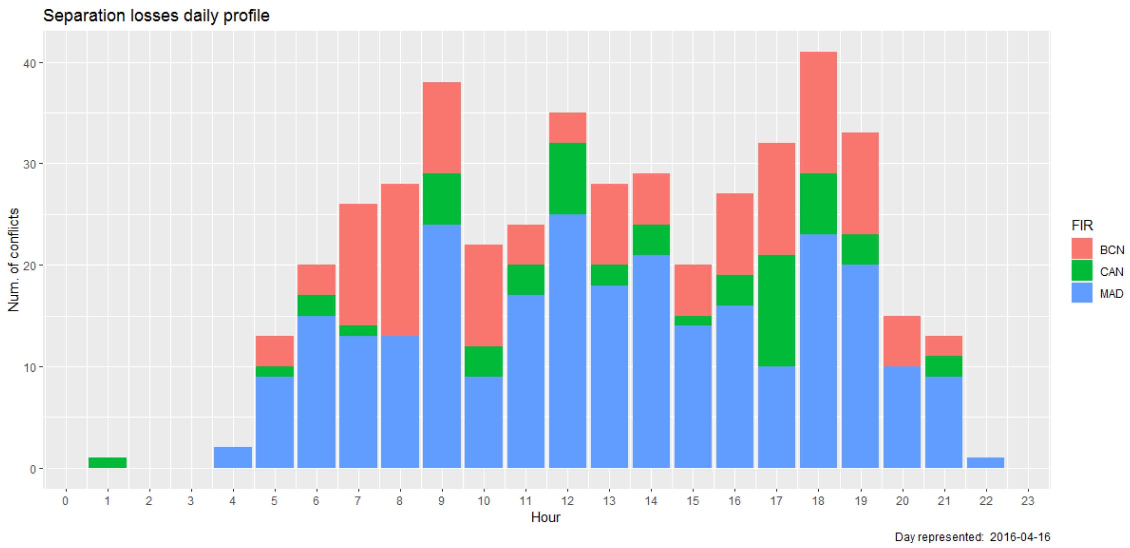


*Figure 28. Separation losses daily profile in FRA (weekend day)*

The same tendency observed in the graph before occur in a weekend day, but in this case, Barcelona does not experiment any increase in number of conflicts, compared with Figure 7. There is still an increase in conflicts in Canarias FIR, which need to be studied in more detail through the rest of the indicators.

### Incidence of separation conflicts among daily hours

If the cumulative incidence of conflicts is observed by hour, as it has been done in Figure 8, a part of observing the aforementioned general reduction in number of conflicts, no more major changes can be seen in the shape of this profile, meaning that the most complex hours still being the same as the previous navigation by waypoints scenario.

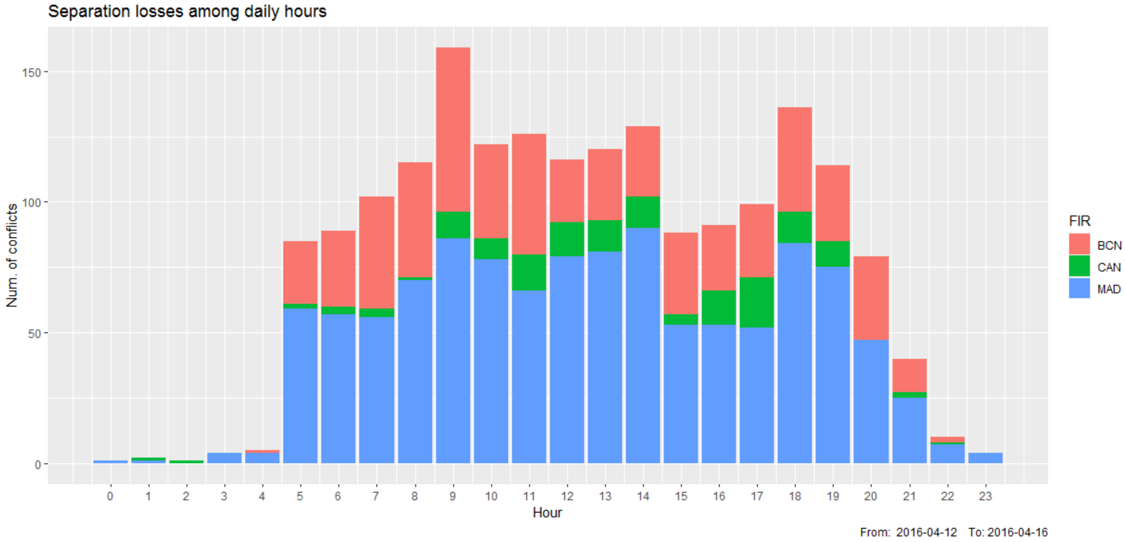


*Figure 29. Total separation losses by hour in FRA*

Despite that, the following graphs allows a more detailed view of the relative weight of the conflicts occurred hour by hour, being the conflicts slightly more spread among the day than in the previous scenario. As it has been seen in the Figure 9, the most concurred hours accounted for a bit more than 40% of the conflicts registered, situation that remains exactly with the same percentage in this case, but observing from 10AM to 2PM roughly equal hourly percentage in 6.25%, situation not seen in the previous scenario.

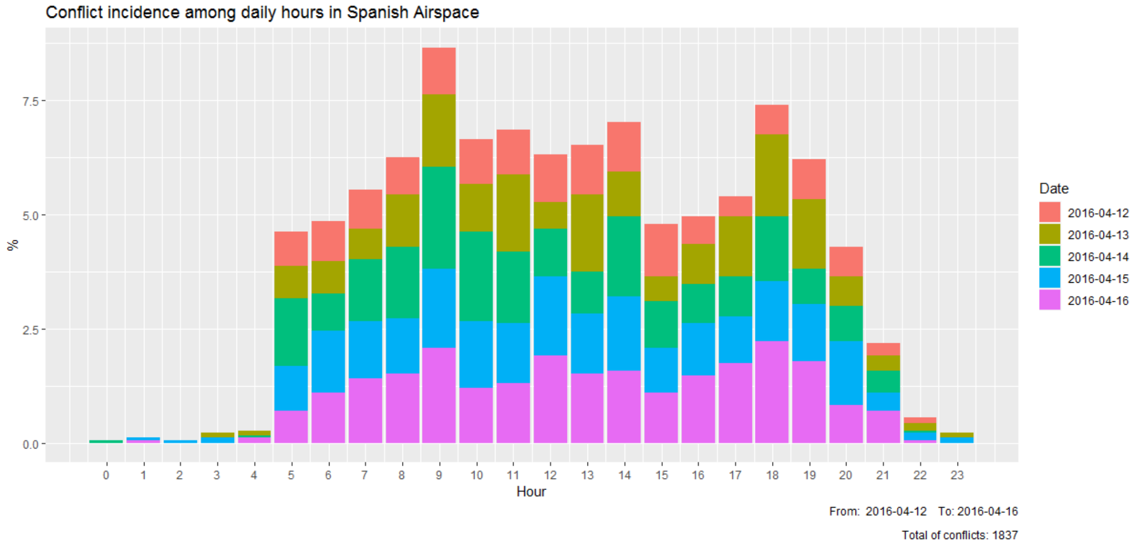


*Figure 30. Conflict incidence among daily hours in Spain (FRA)*

Observing the conflicts hourly incidence FIR by FIR, there is an increase of this relative indicator in the peak hour (from the previous 10% to the actual 12.5%) at expense of a reduction in relative conflict incidence during the less concurred hours, in the late morning and in the afternoon: hours from 12AM to 5PM. Observing daily contributions, there is not relevant changes with Figure 10 apart of a small increase in the relative presence of conflicts on Wednesday 13th at expense of a small drop in relative conflicts occurrence on Friday 15th.

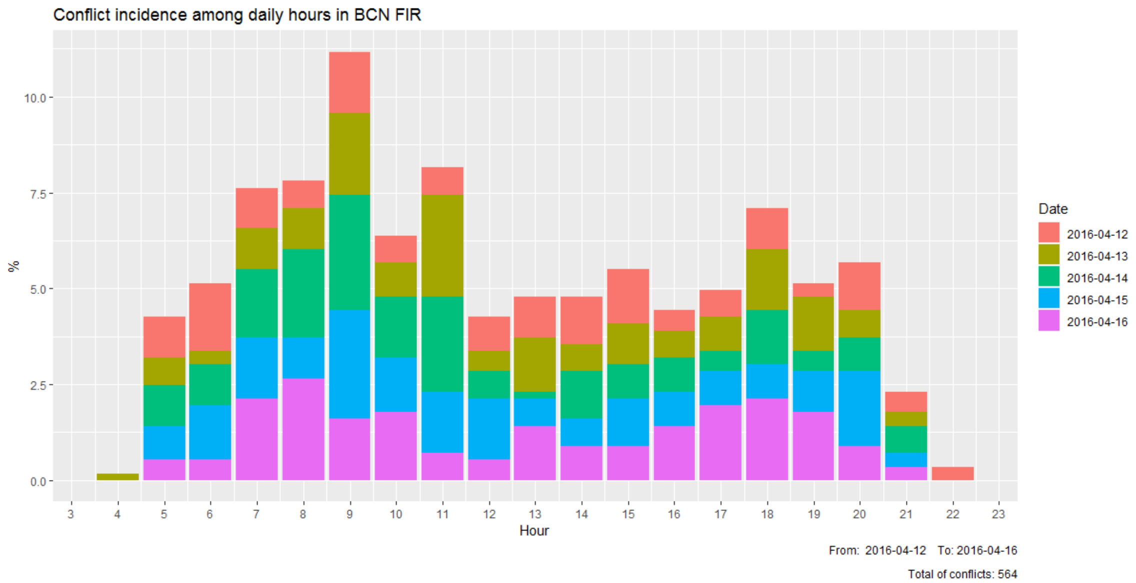


*Figure 31. Conflict incidence among daily hours in BCN FIR (FRA)*

In this scenario, the 564 conflicts registered in Barcelona FIR account for a 30.7% of the Spanish conflicts, a percentage slightly superior than the previous 29.3%.

Considering Madrid profile, despite is not as clear than in Barcelona, the same tendency can be observed, being the most conflictive hours with higher presence in relative terms -e.g. from 9AM to 1PM- but peaks are softened in this case, being the relative impact of each hour more spread than in non-FRA scenario.

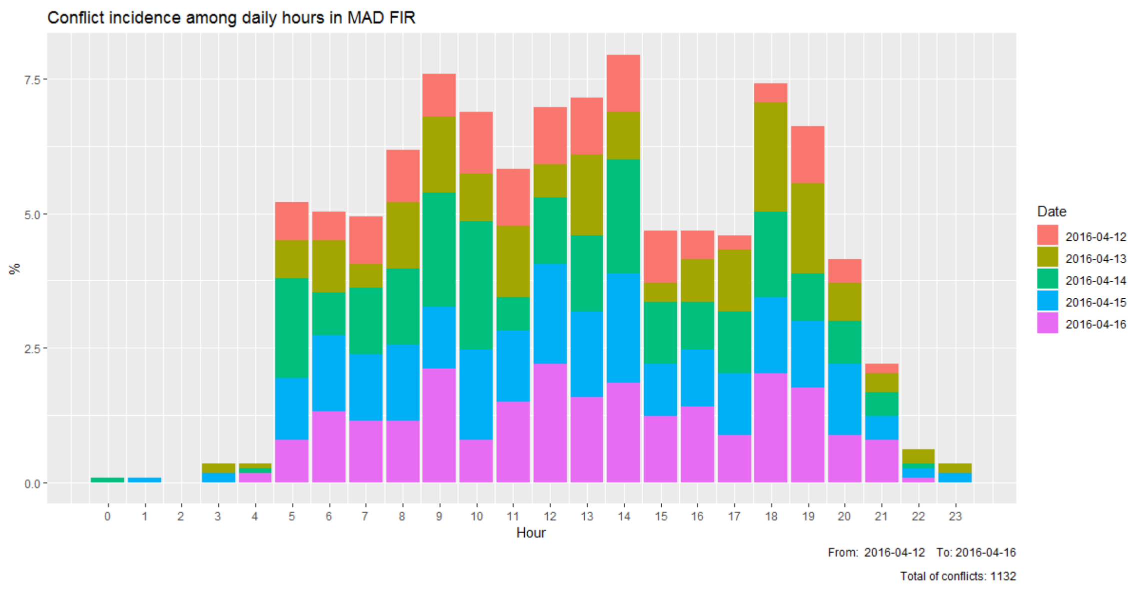


*Figure 32. Conflict incidence among daily hours in MAD FIR (FRA)*

Considering the 1132 conflicts reported in the FRA simulation for Madrid, this airspace constitutes the 61.6%. Unlike the occurred in Barcelona, it represents less than the previous scenario, where Madrid accounted for the 65.4% of the total Spanish conflicts.

Regarding Canarias, the conflicts profile presents a more stable pattern than the one seen in Figure 12, but changes in some aspects can be highlighted: daily distribution is notably different and there are major changes the relative importance of some hours, like the drop at 3PM and the raise in 5PM in comparison with non-FRA scenario.

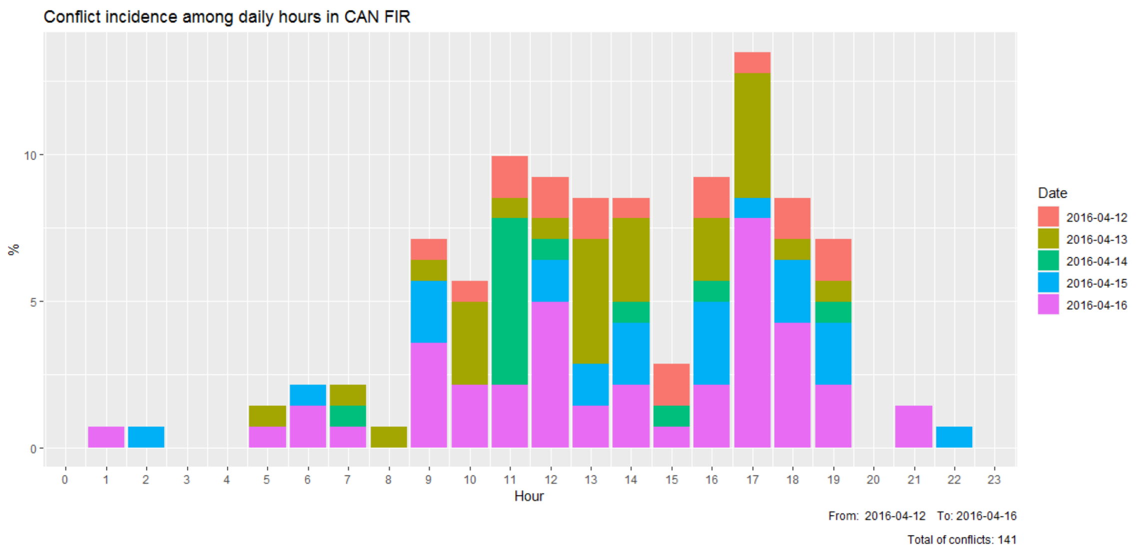


*Figure 33. Conflict incidence among daily hours in CAN FIR (FRA)*

Lastly, the total number of conflicts detected trough this simulation in Canarias has increased, passing from the previous 135 to the actual 141 conflicts, which represent a 7.7% of the Spanish FRA conflicts against the 5.3% present in non-FRA for this FIR.

### Density of conflicts among daily hours

In general terms, as the overall number of conflicts has dropped for the FRA scenario maintaining the same traffic figures, the density of conflicts graphs present lower values for all cases.

Concerning their shape, in the case of Barcelona is pretty different, observing only some similarities in the hourly growth and degrowth tendency of each day profile.

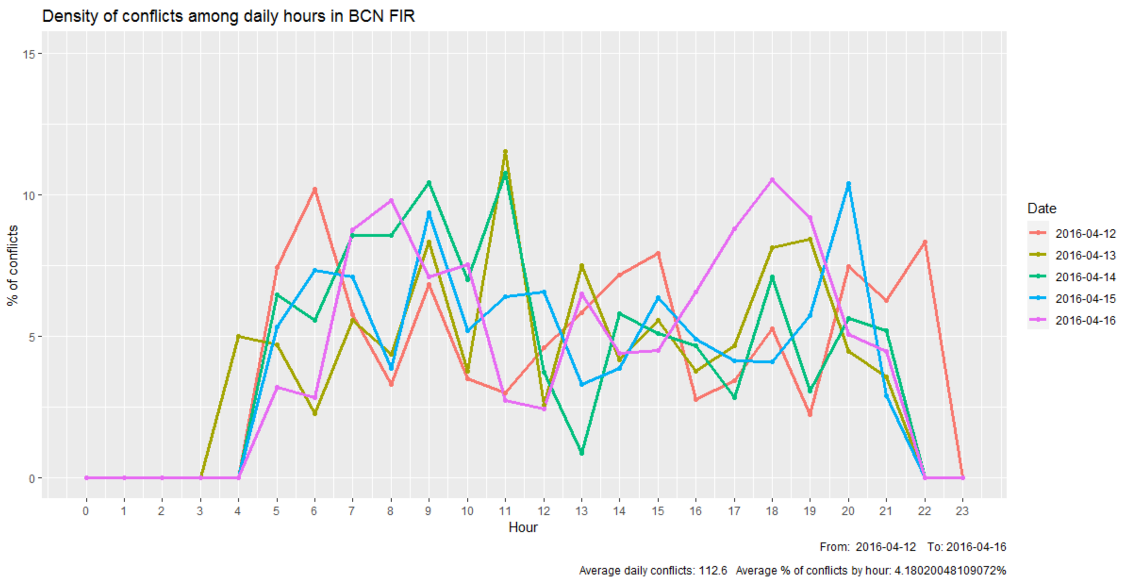


*Figure 34. Density of conflicts among daily hours in BCN FIR (FRA)*

On the other hand, Madrid graph is more similar with its homologous, the Figure 14, having very similar patterns in most of the lines, representing daily density of conflicts. It is worthy to mention than peaks observed on Saturday 16th for the previous scenario are not present in this case, being a FRA clearly beneficial for Madrid FIR in density of conflicts reduction.

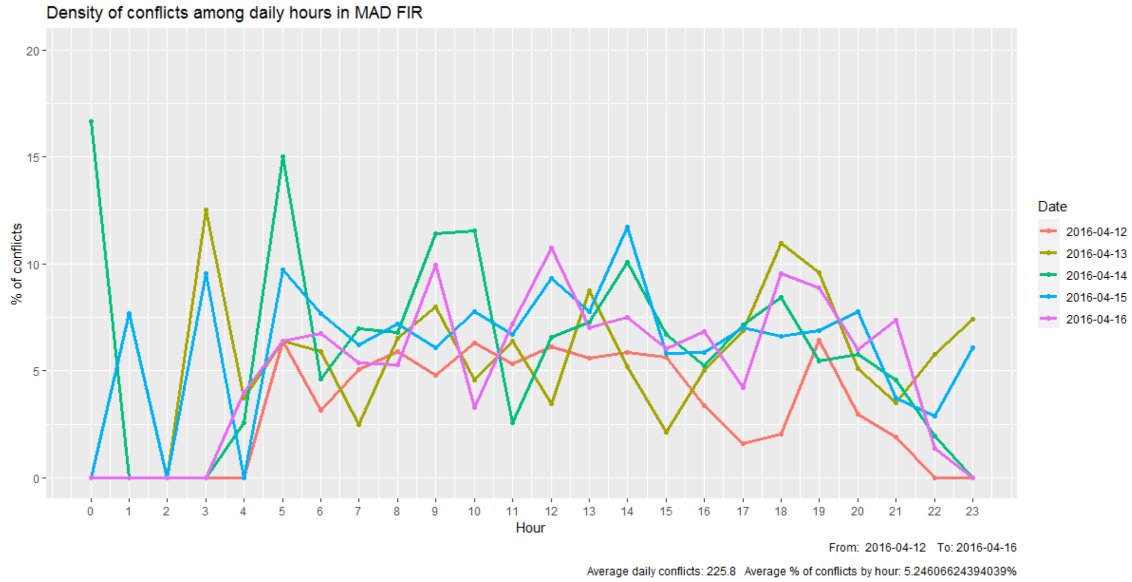


*Figure 35 . Density of conflicts among daily hours in MAD FIR (FRA)*

For this case in Canarias, there is a higher density of conflicts per hour compared with the previous scenario, specifically 2% higher. The represented profile, with relative presence of conflicts among total operations present in the airspace remains unstable due to the effect of a low presence of flights and a high relative relevance of a single conflict in Canarias FIR environment.

It is also noticeable that the figure below, compared with its equivalent Figure 15, present exactly the same picture from 0AM to 8AM, being most of the differences caused by FRA implementation observed during the solar day.

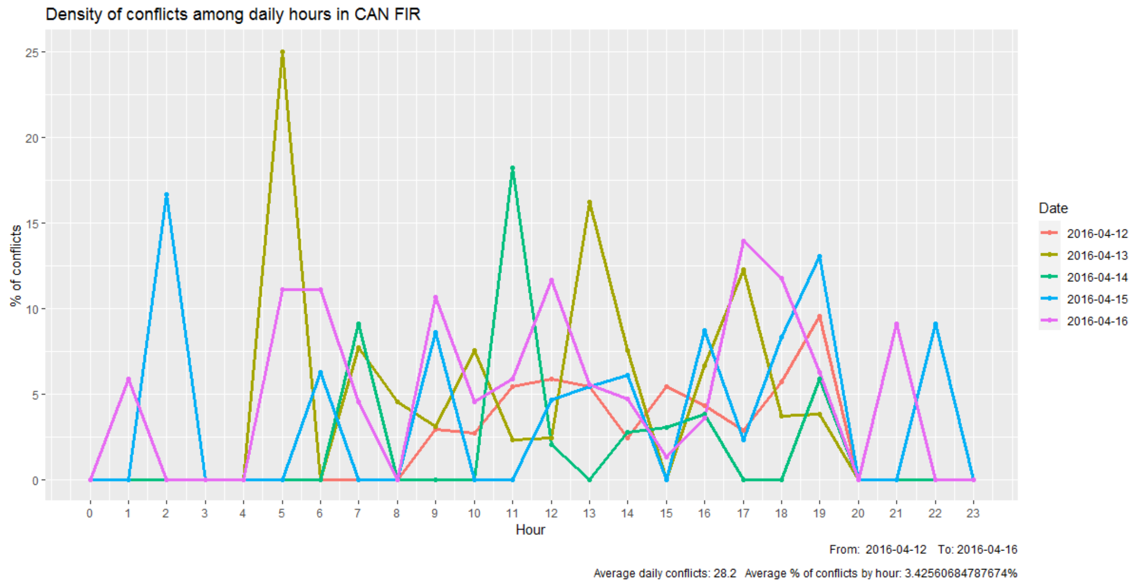


*Figure 36 . Density of conflicts among daily hours in CAN FIR (FRA)*

**Geographic distribution of the conflicts observed**

The fully FRA scenario simulated eliminates flights by air routes, so a priori, a more randomized distribution of the conflicts is expected at geographical level for all Spanish airspaces.

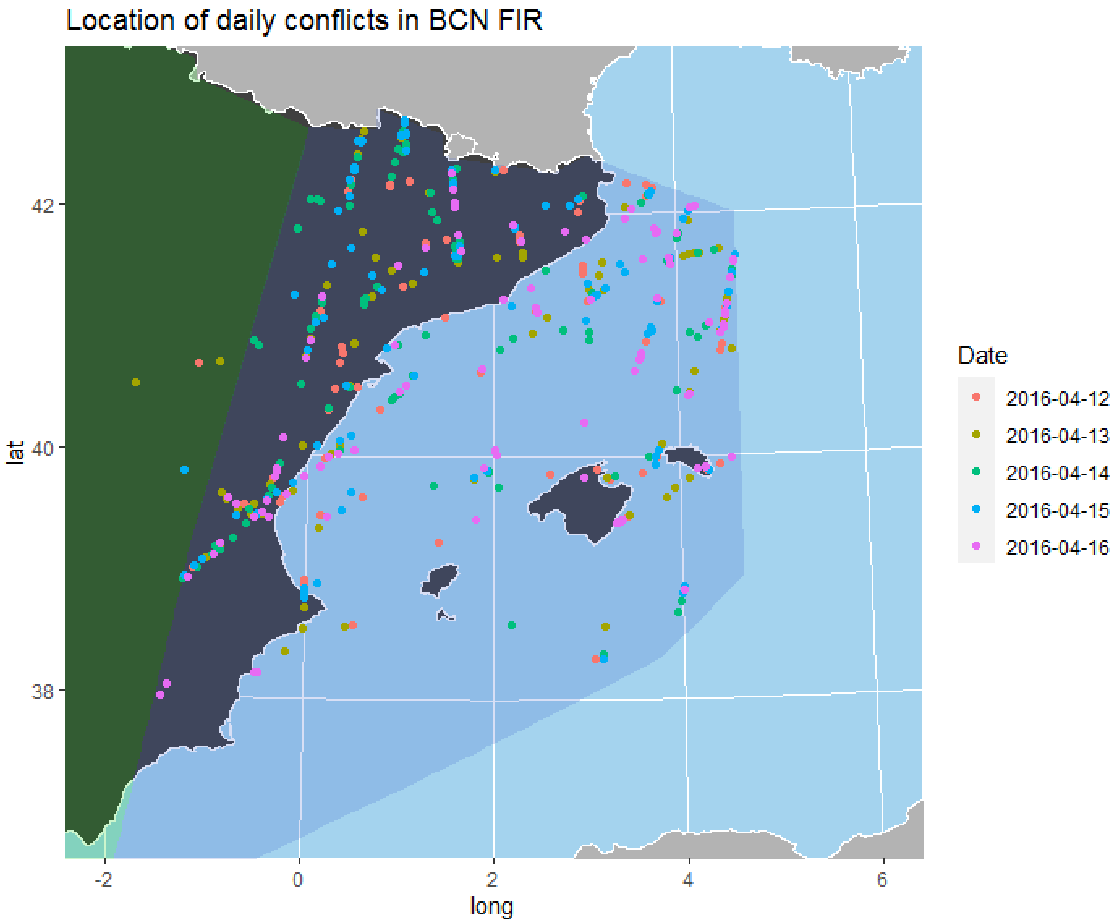


*Figure 37. Location of daily conflicts by date in BCN FIR (FRA)*

Indeed, this is the main conclusion extracted when FRA scenario conflicts are represented over a map in Barcelona FIR, where despite some lines can be observed overlapping all the conflicts, this tendency is pretty more vanished compared with Figure 16.

Lines continue appearing in some cases because, as it is shown in Figure 17, some air routes are straight and the entry and exit point of several flights are coincident. Also, FRA simulation has been done using data from flights not flying under FRA conditions what it means that, notable differences can only be appreciated in the interior of the FIR unit for flights that do not follow a straight trajectory between the navpoints along their path.

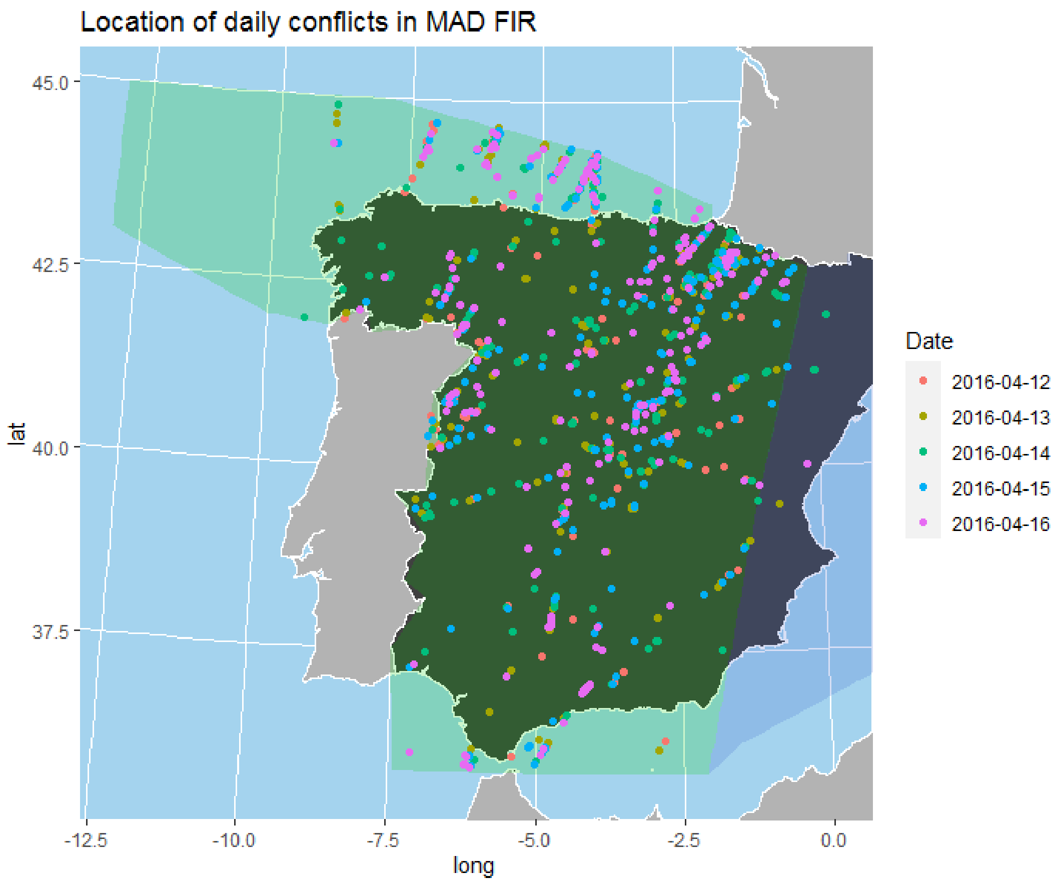


*Figure 38. Location of daily conflicts by date in MAD FIR (FRA)*

Madrid FIR presents also the same tendency, having a more randomized distribution of points. What is really noticeable for this case is the concentration of points, specially from Friday 15$^{th}$ and Saturday 16$^{th}$ in the French and the Portuguese borders, being as a possible cause, the interference of cross-country ATC procedures.

Despite this, the mentioned fact cannot be explained fully just with the flight data available and SUAs and meteorological information about the special events taken place these days would be needed to have a complete picture and determine certainly the cause of the observed concentration of conflicts.

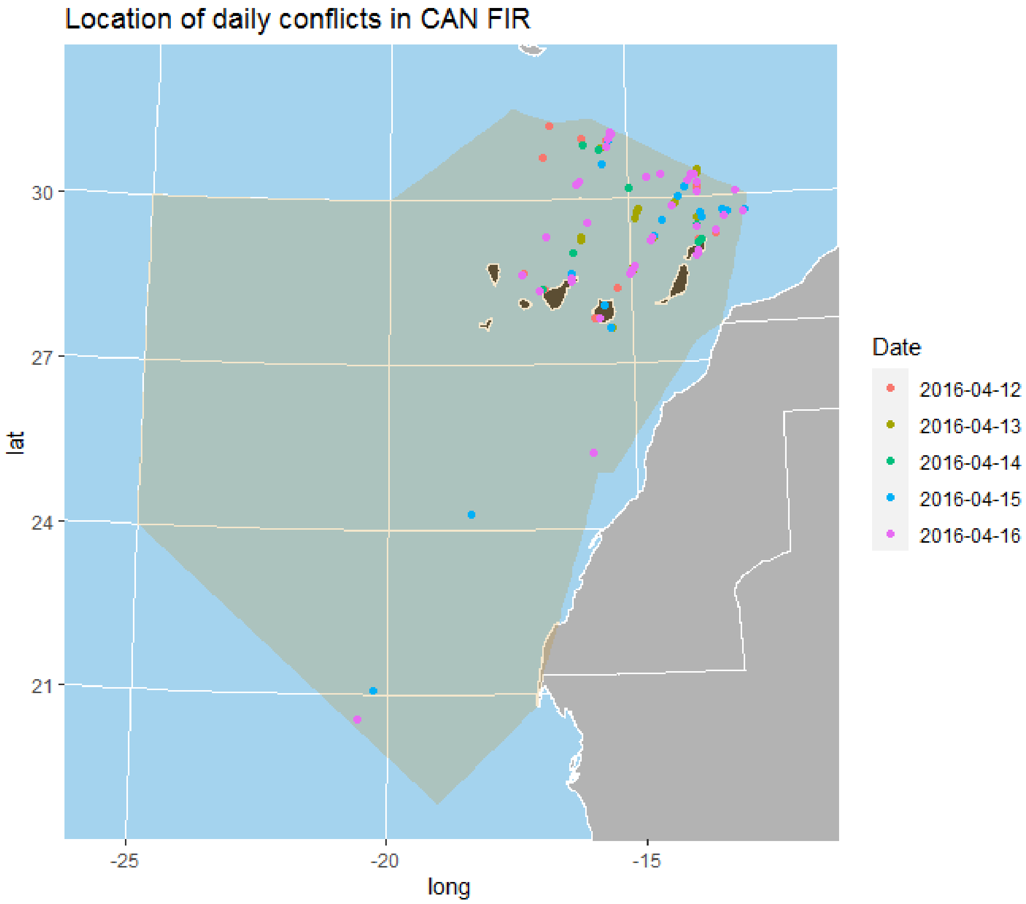


*Figure 39. Location of daily conflicts by date in CAN FIR (FRA)*

Finally, the situation in Canarias is pretty similar as the one shown in Figure 19, being most of the conflicts located at the N-E boundary of the FIR and shaping straight trajectories -a bit more diffused in this scenario- when overlapped.

**Severity of the conflicts distributed among daily hours and geography**

Concerning the severity of the conflicts, Barcelona present the same tendency as the non-FRA case, being low severe the most occurred conflicts and in second place medium and very high severity conflicts with similar values.

As the previous scenario, there is a peak in very high conflicts in the early morning, but in this case the peak occurs one hour before, being 8AM the worst hour in terms of safety. Despite there is less conflicts than in non-FRA scenario, the mean severity punctuation of all the separation losses is 2.5 points higher in this case, which is not much, but represent that the conflicts occurred in a FRA environment need to be monitored and mitigated carefully with the ATS systems available when the new environment is fully implemented.

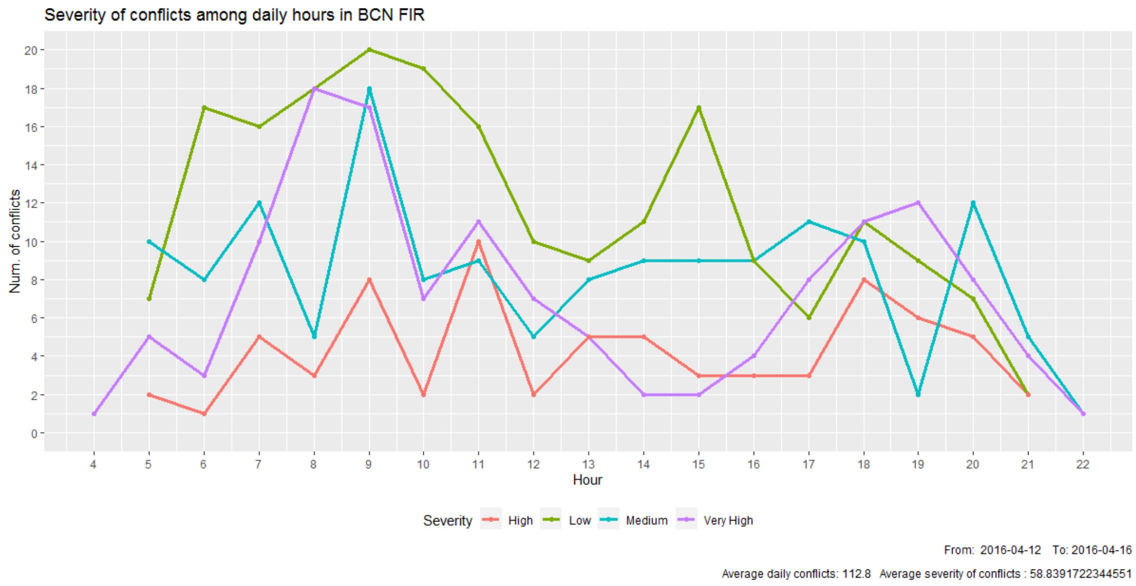


*Figure 40. Severity of the conflicts among daily hours in BCN FIR (FRA)*

In the FRA scenario in Madrid FIR, not only there are also less conflicts than in the previous scenario, but there are notably less conflicts classified as very high severity conflicts. Hourly profiles for all categories follow similar tendencies than the ones in Figure 21.

Average severity of conflicts is, for this scenario, 4 points lower than for the previous one which, of course is a positive effect of FRA implementation in a wide and concurred airspace like Madrid FIR.

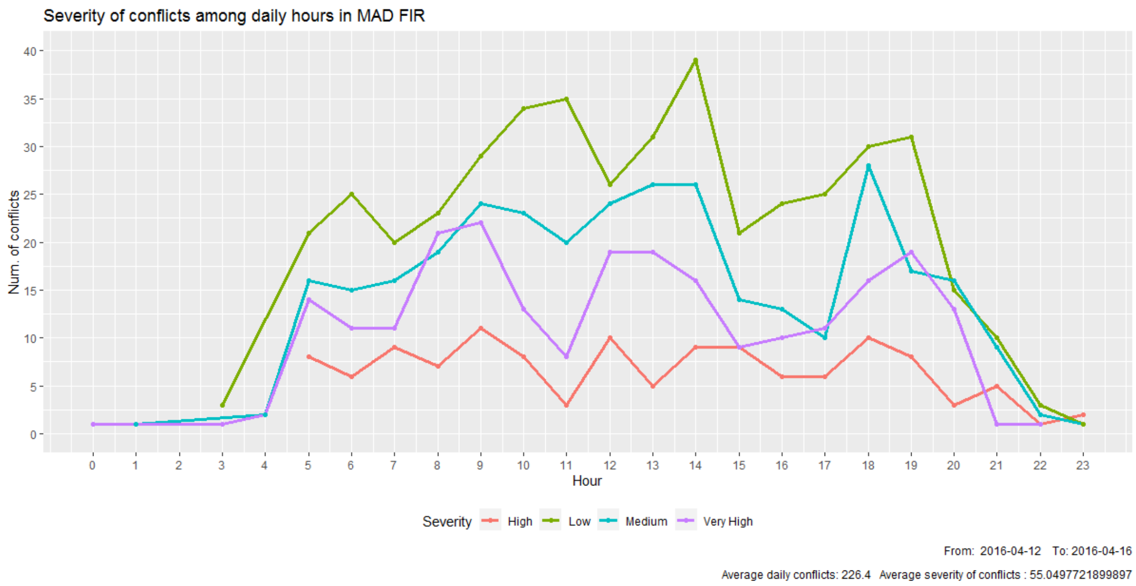


*Figure 41. Severity of conflicts among daily hours in MAD FIR (FRA)*

In Canarias, despite the mean severity of conflicts has also fallen for 3 points in this case, it is worrying that, as it can be seen in the following graph, the relative weight of Very High severity conflicts is much higher, at expenses of a decrease in the conflicts of all the other categories.

Considering all the data obtained from them in the analysis, it can be said that the majority of very high severity conflicts are registered the days 15th and 16th of April, some of them involve parallel conflicts with 3 different flights involved and time factors are quite high in some of them, existing conflicts maintained for more than 30 min near TMA Canarias.

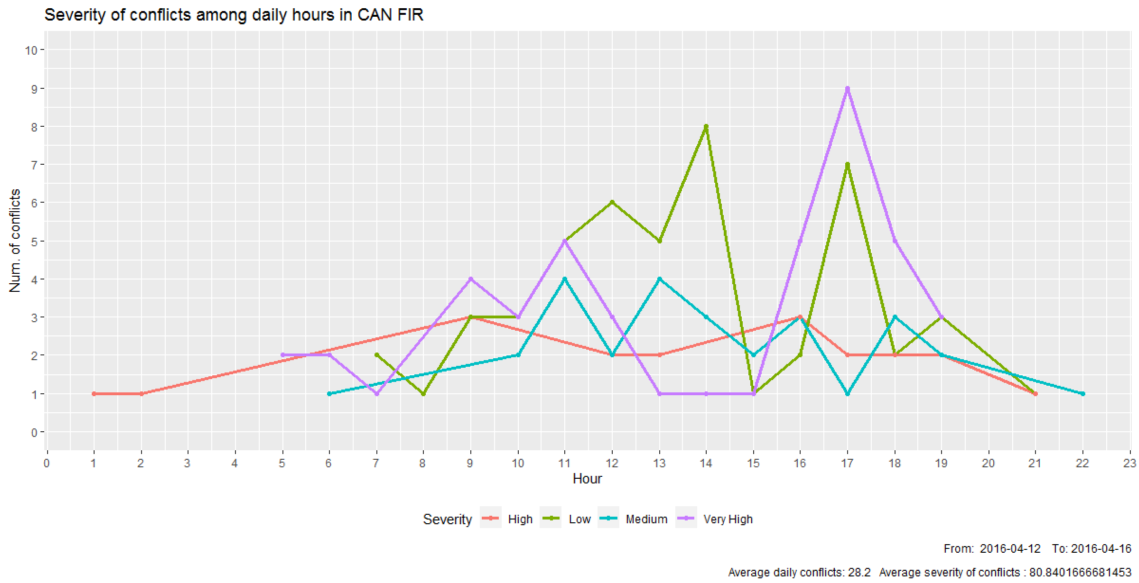


*Figure 42. Severity of conflicts among daily hours in CAN FIR (FRA)*

As said previously, Canarias would require a more detailed analysis, since the discretization done in this study is not precise enough to cover the small sample present in Canarias with the desirable detail to extract definitive conclusions.

Despite that, the results in Canarias represent a first approach to compare with an hypothetic more specific studio, which would require more computational power and is out of the scope of this preliminary analysis of FRA implementation in Spain.

Considering the conflicts severity for its geographical location, conclusions extracted in the previous scenario remains valid, at least in Barcelona and Madrid FIRs, although at it has been pointed previously, conflicts are notably more scattered in this scenario.

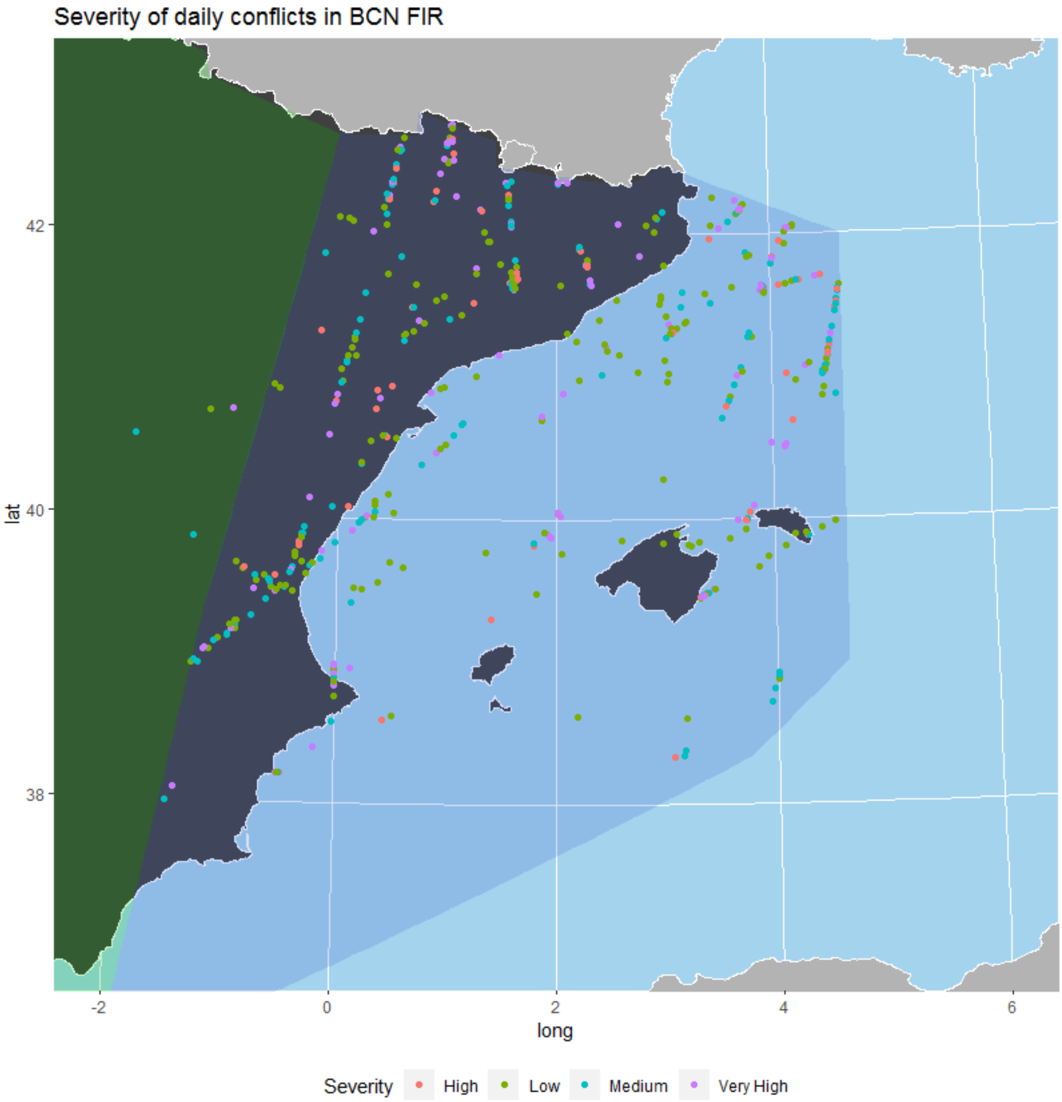


*Figure 43. Location of daily conflicts by severity in BCN FIR (FRA)*

In this scenario, like in non-FRA homologous figure, very high severity conflicts tend to be concentrated in the north boundary of the FIR. Some of them appear also around Valencia node and there can be seen also concentrations of purple over Cap de la Nao, the cape located in the north of Alacant or at north-west of Mallorca island.

There's not any specific pattern identified for this case and there are not concentrations that require more special attention that the current ATC conflict mitigation procedures.

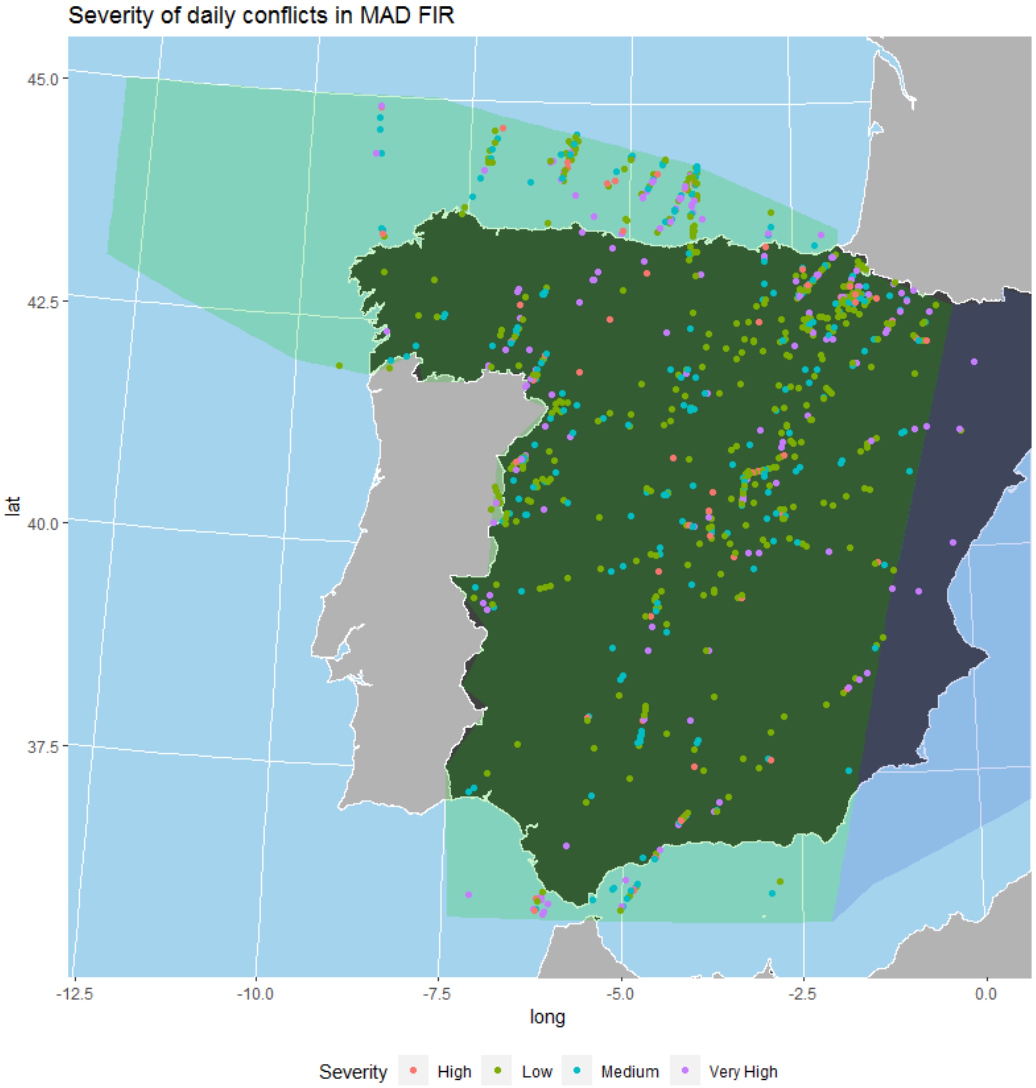


*Figure 44. Location of daily conflicts by severity in MAD FIR (FRA)*

Regarding Madrid, there can be seen concentrations of very high severity conflicts on the FIR boundary touching with France, especially in Cantabric region. The mitigation treatment of them implies, among other measures, enhanced cooperation with the French ATC network and the development of cross-country FRA scheme, which design will be certainly more complex than for other regions, including several intermediate points and other kind of constraints affecting flight trajectories.

It is also worthy to mention that some despite some new small concentrations of conflicts are formed in this scenario (e.g. at the west of Gibraltar strait) the resulting picture of a FRA implementation in Madrid FIR is extremely optimistic, as several concentrations of conflicts present in the non-FRA equivalent Figure 24 are vanished here.

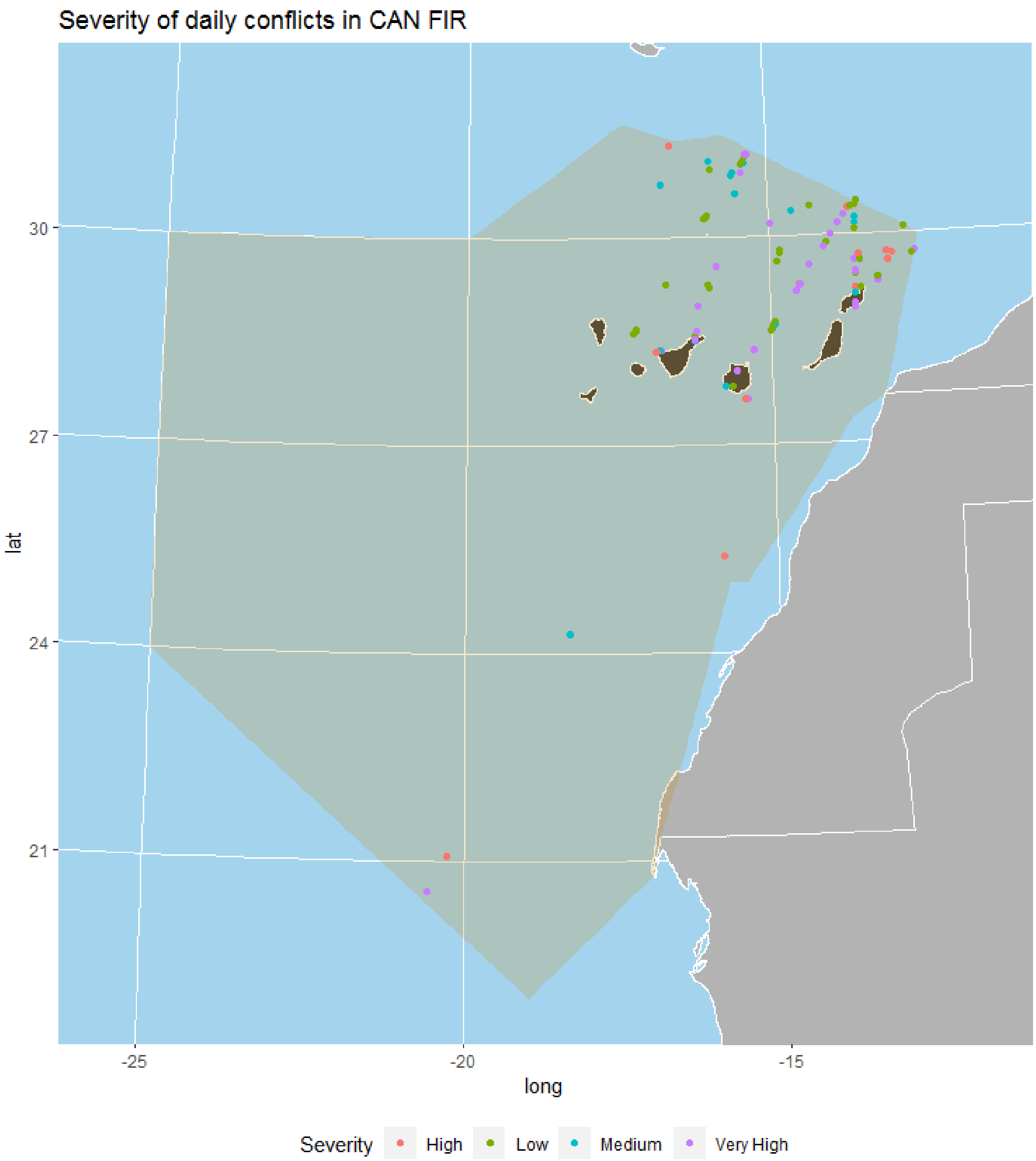


*Figure 45. Location of daily conflicts by severity in CAN FIR (FRA)*

Finally, the case of FRA implementation over Canarias is unclear and the situation is pretty similar to the existing one with no FRA implementation. Although, it can be appreciated in this scenario that very high conflicts, which represent a higher percentage of the total, are mostly located on the east side of the area where conflicts occur, phenomena that is not observed in the homologous Figure 25.

### Flight efficiency analysis results

In order to assess the flight efficiency of the air navigation in each scenario, distances flown are computed for each flight along its route over Spain, obtaining mileage data, represented in the following indicators.

**Overall mileage flown**

The first parameter to consider is the total or overall mileage flown, which accounts by the sum of the distances flown by each flight over Spain every day of analysis.

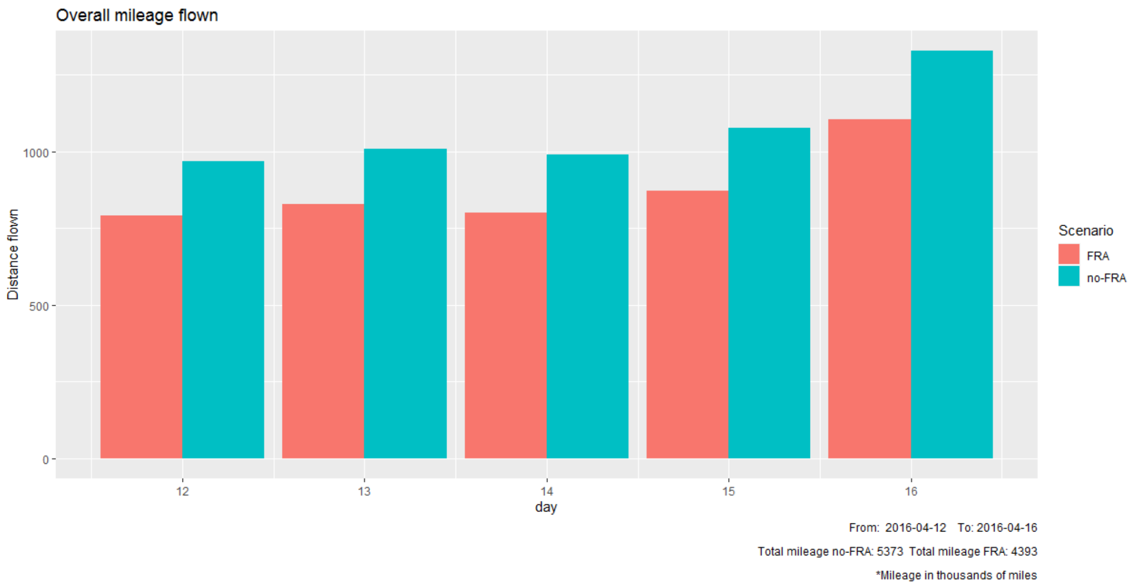


*Figure 46. Overall mileage flown in Spain*

In the figure, distances are represented in thousands of Nautical Miles, being the mean daily distance flown by waypoint-based routes around 1 million nautical miles (in working days) while the daily mean in FRA scenario stays around 750 thousand nautical miles, what is a 25% less.

To compute the effect of FRA in reducing the distance flown, the total mileage flown in both scenarios has been computed, allowing the calculation of the gross reduction of distance flown caused by FRA.

$$Distance\ saved = (5373 - 4393) * 10^3 = 980 * 10^3\ NM$$

$$\%\ of\ Distance\ Reduced = \frac{5373 - 4393}{5373} * 100 = 18.24\ \%\ (less)$$

In total, the implementation of FRA in the time period analyzed, caused a reduction of 18.24% of the distance flown, improving greatly the EnRoute flight efficiency.

**Average mileage reduction per flight**

In order to account the reduction achieved in terms of distance saved per flight and to locate FIR units where is more likely to achieve greater improvements in flight efficiency, the following figures are obtained and represented:

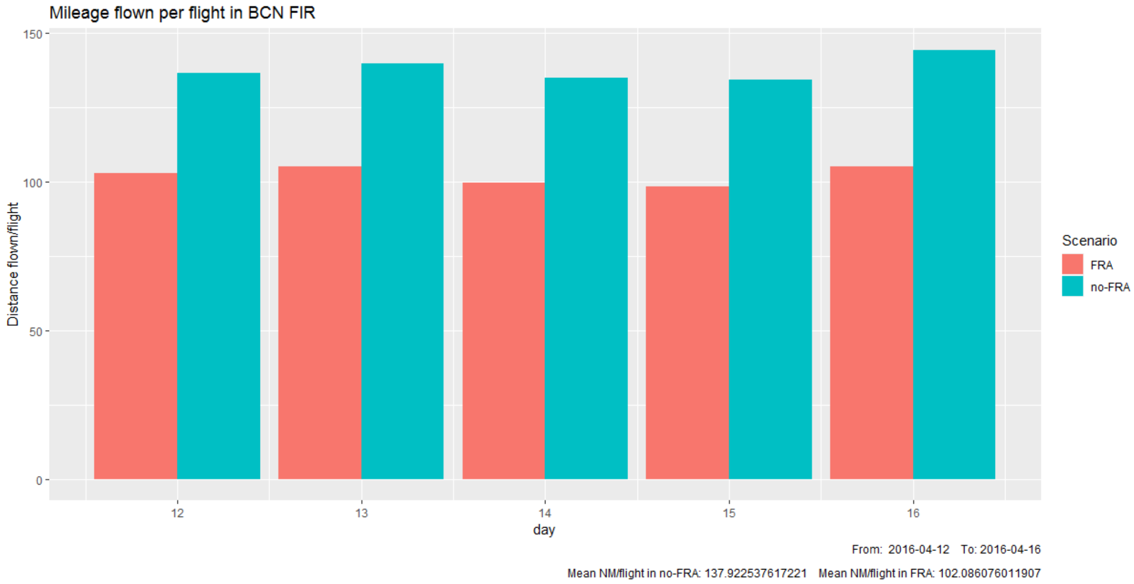


*Figure 47. Mileage flown per flight in BCN FIR*

In the case of Barcelona, as it can be observed also in Madrid trough the figure below, the mileage reduction per flight is fairly constant and its dependance of the day analyzed is weak, at least with the sample taken in this study.

As it can be seen from the graph, each flight passing through Barcelona's airspace travels an average of almost 138 nautical miles in the case of a navpoint-based navigation and 102 nautical miles in the FRA scenario simulated. This represent a reduction of 26% of the distance flown by flight, which is a very significative percentage.

Of course, in a real implementation, the scenario presented would be affected by SUAs, meteorological successes and the influence of the present TMAs, which would probably generate the need of re-routings in some operations, making the reduction percentage obtained from this "perfect FRA scenario" drop slightly.

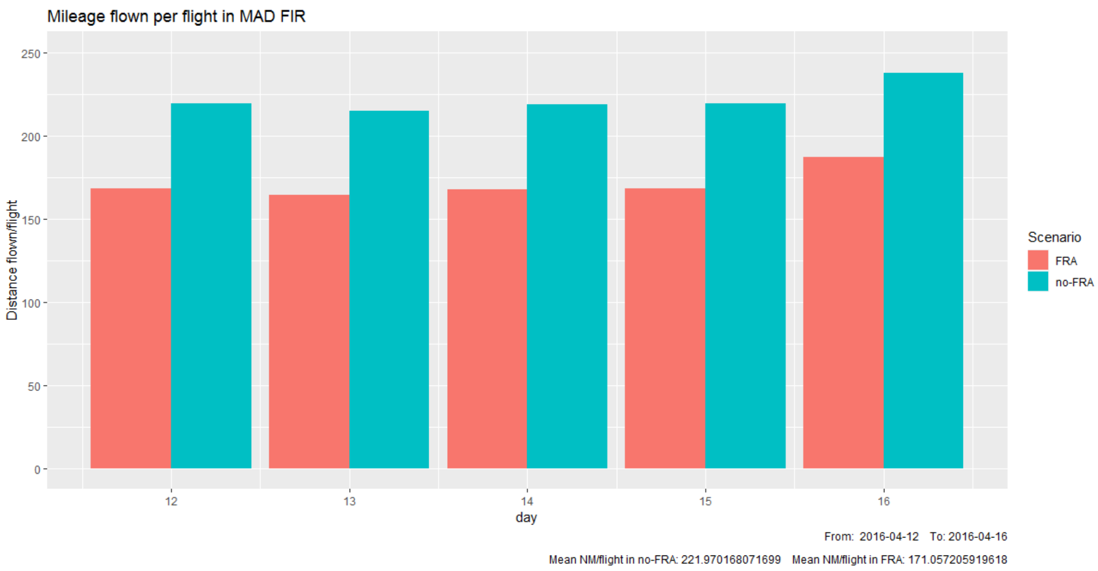


*Figure 48. Mileage flown per flight in MAD FIR*

Exactly the same situation occurs for Madrid, where the optimistic reduction of distance flown per flight is found at 23%.

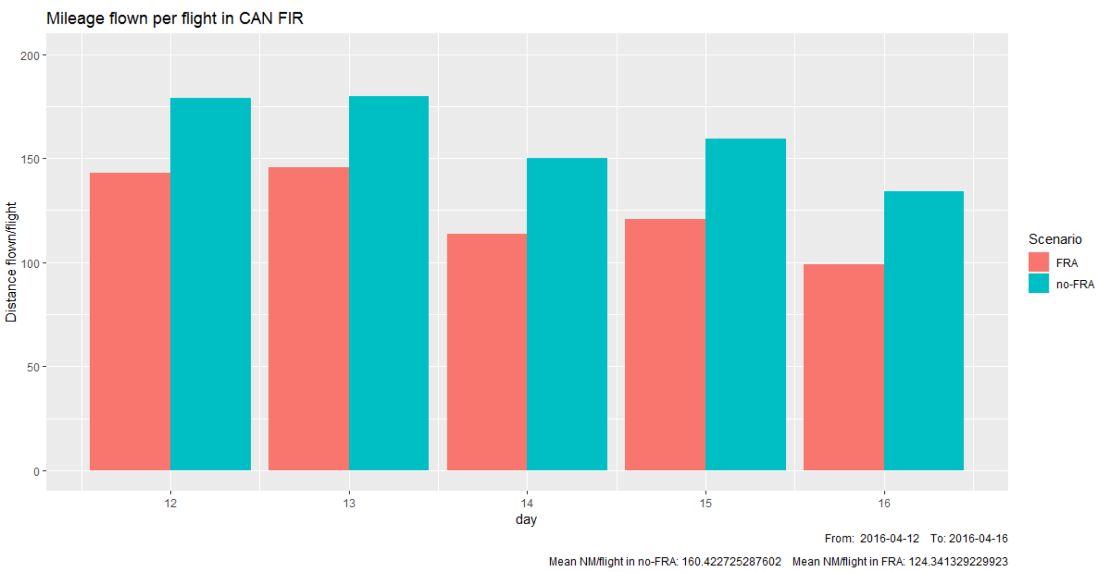


*Figure 49. Mileage flown per flight in CAN FIR*

Finally, in the case of Canarias FIR, there are more differences between days over mileage flown per each flight. Despite that, relative distance reduction caused by FRA implementation is fairly constant at 22.5%, which is a notable percentage that makes the implementation of a Free Route, despite it still have unclear effects on safety in this airspace region, an improvement worthy to be investigated in more detail.