Visual Analytics of (Aircraft) Trajectory Data

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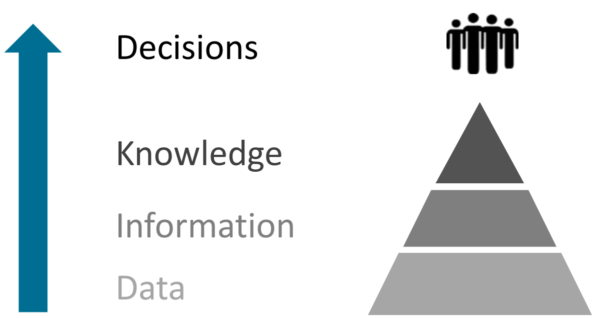
DART datAcron

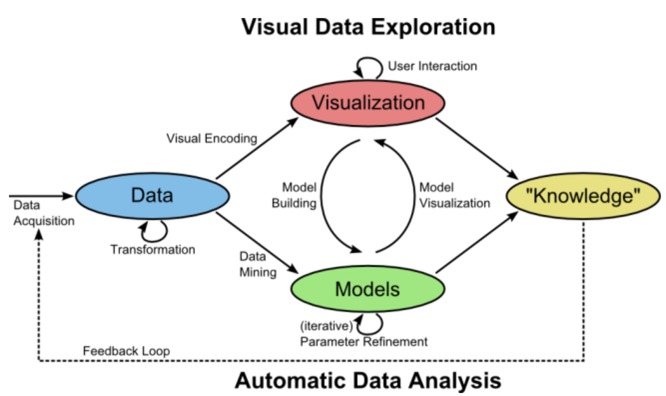
Visual Analytics

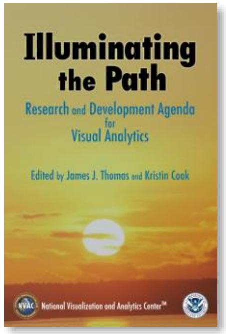
The science of analytical reasoning facilitated by interactive visual interfaces.

Visual analytics tools and techniques are used to

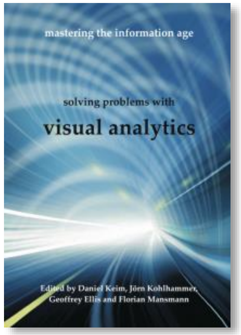
- Synthesize information and derive insight from massive, dynamic, ambiguous, and often conflicting data
- Detect the expected and discover the unexpected
- Provide timely, defensible, and understandable assessments
- Communicate assessment effectively for action







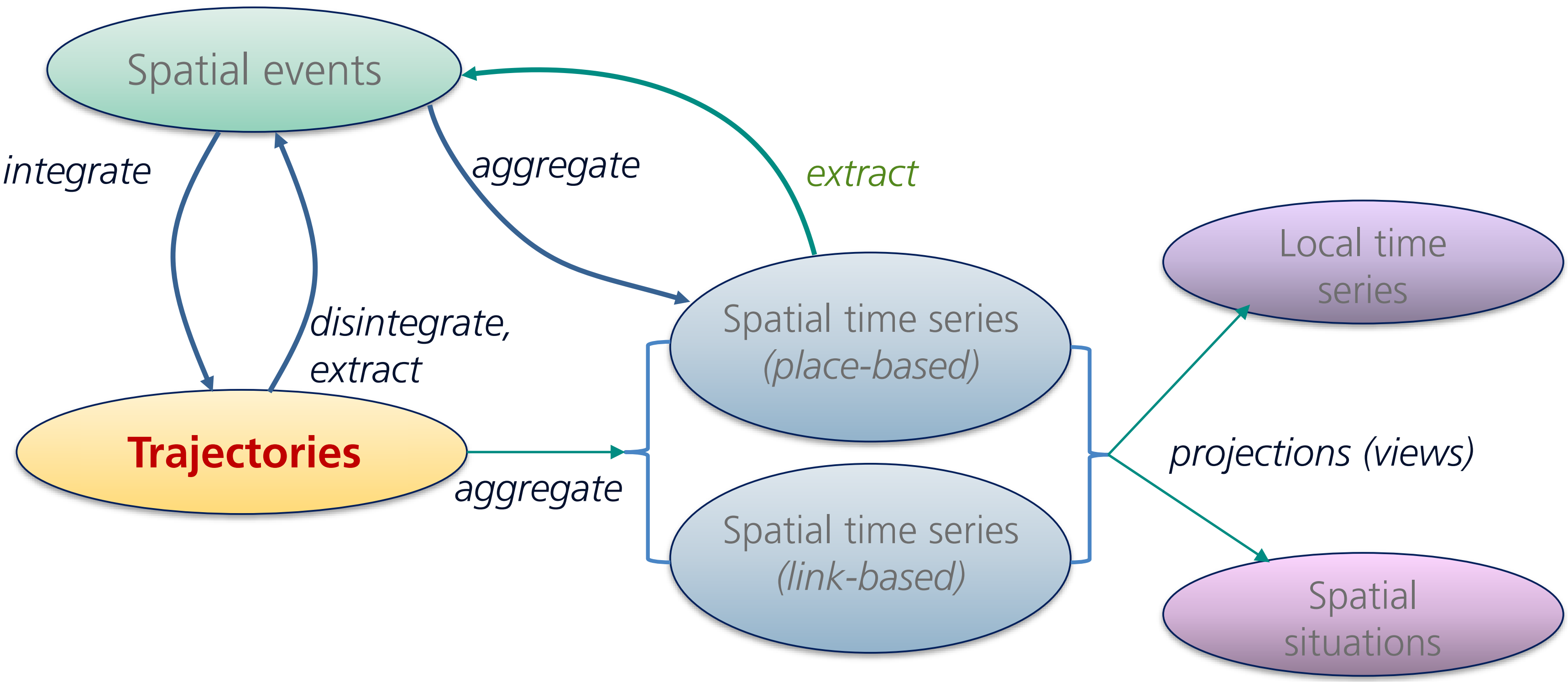
IEEE Computer Society 2005
http://nvac.pnl.gov/



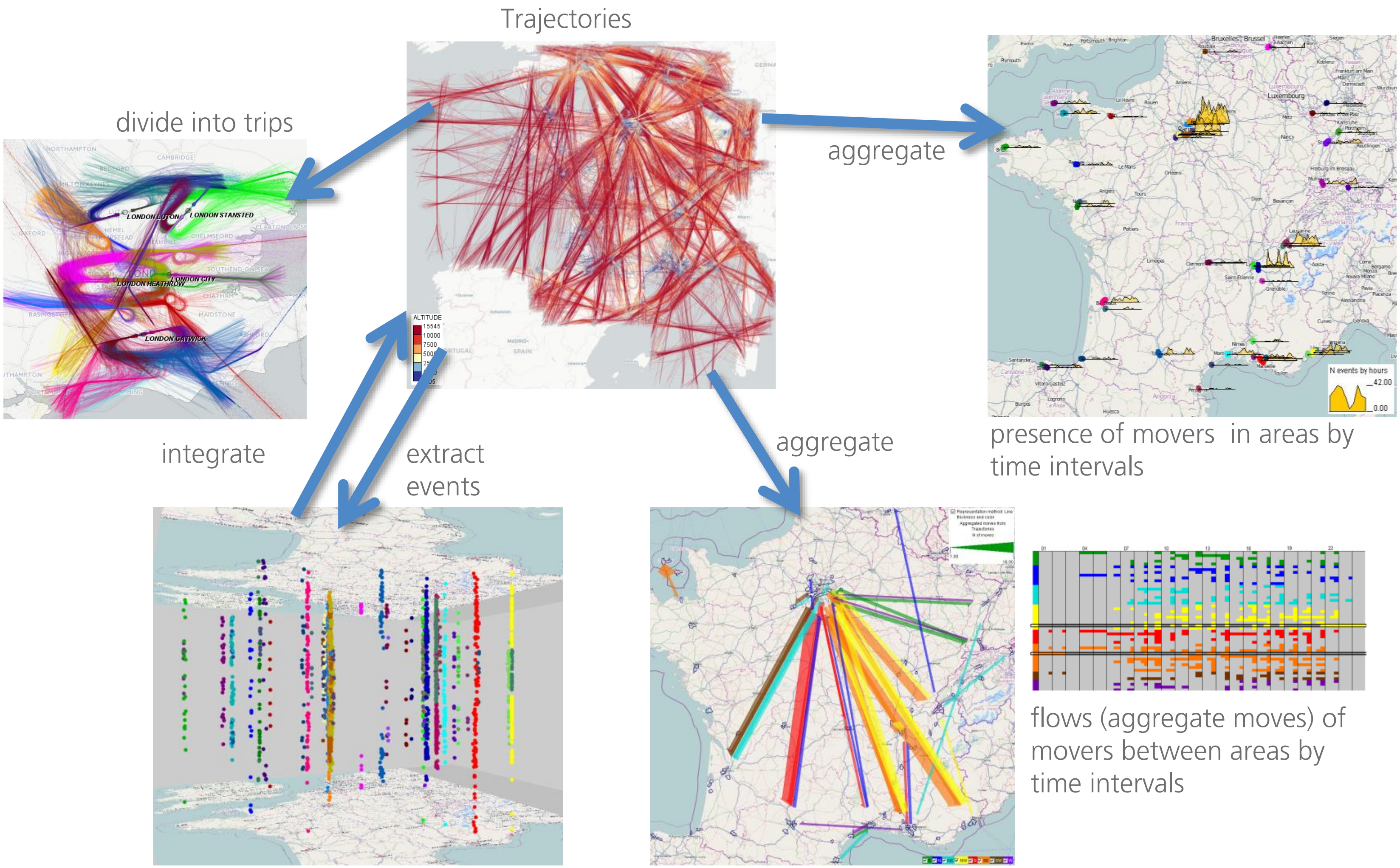
EuroGraphics 2010
http://www.vismaster.eu/book

Visual Analytics of Movement Data: Principal Transformations

Different representations of movement data suitable for different analysis tasks / reporting requirements



Principal Transformations of Movement Data

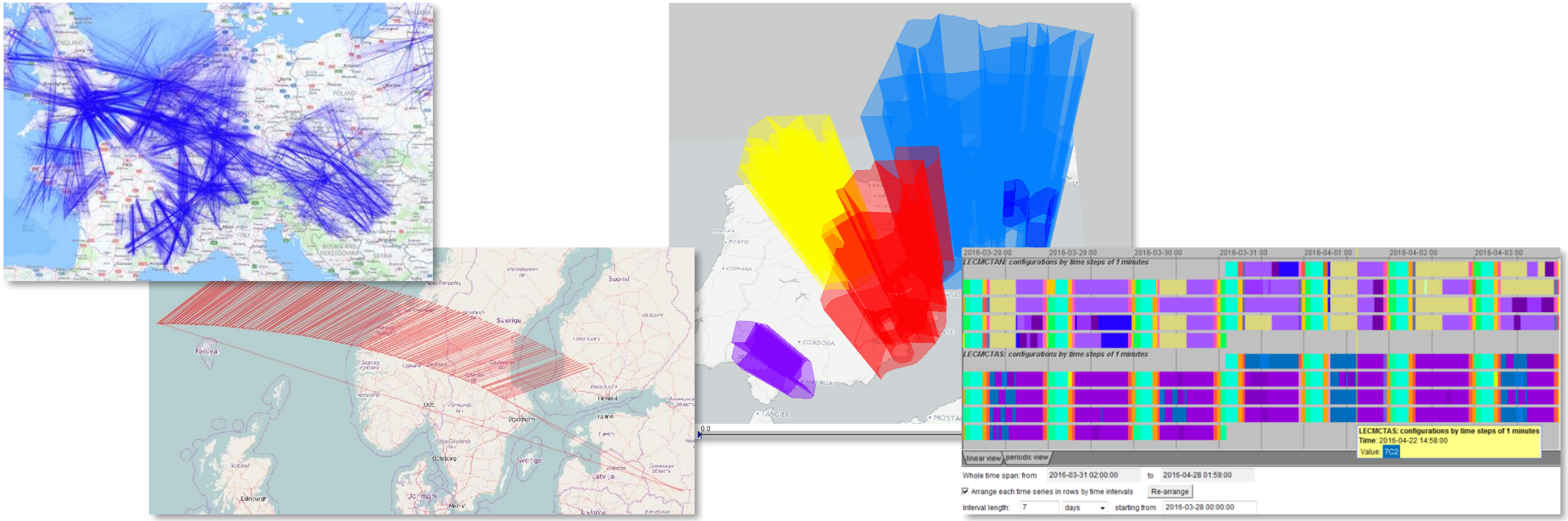


Visual Data Exploration – Data Understanding & Data Quality

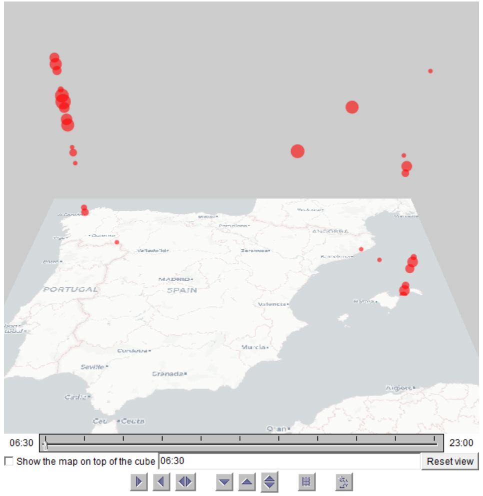
Movement happens in context – airspace design is a 4D spatio-temporal puzzle

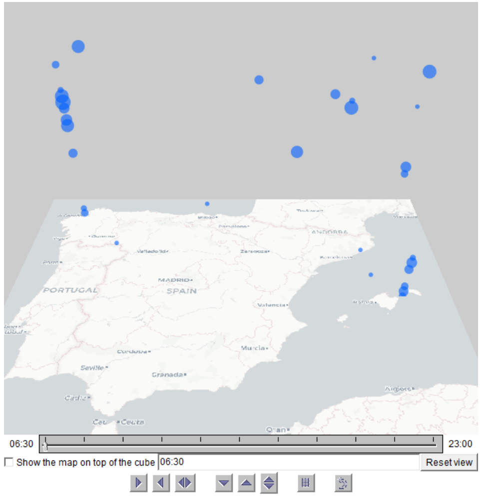
Identification of most common types of errors, data gaps, ingestion problems

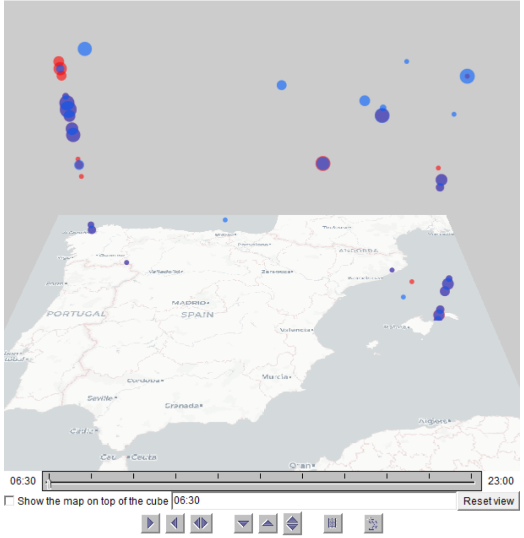
- ADS-B data: positional messages aggregated into trajectories
- Flight Plans + Regulations
- DDR Airblock/Configuration/Capacity data



Visualizations of DART solutions

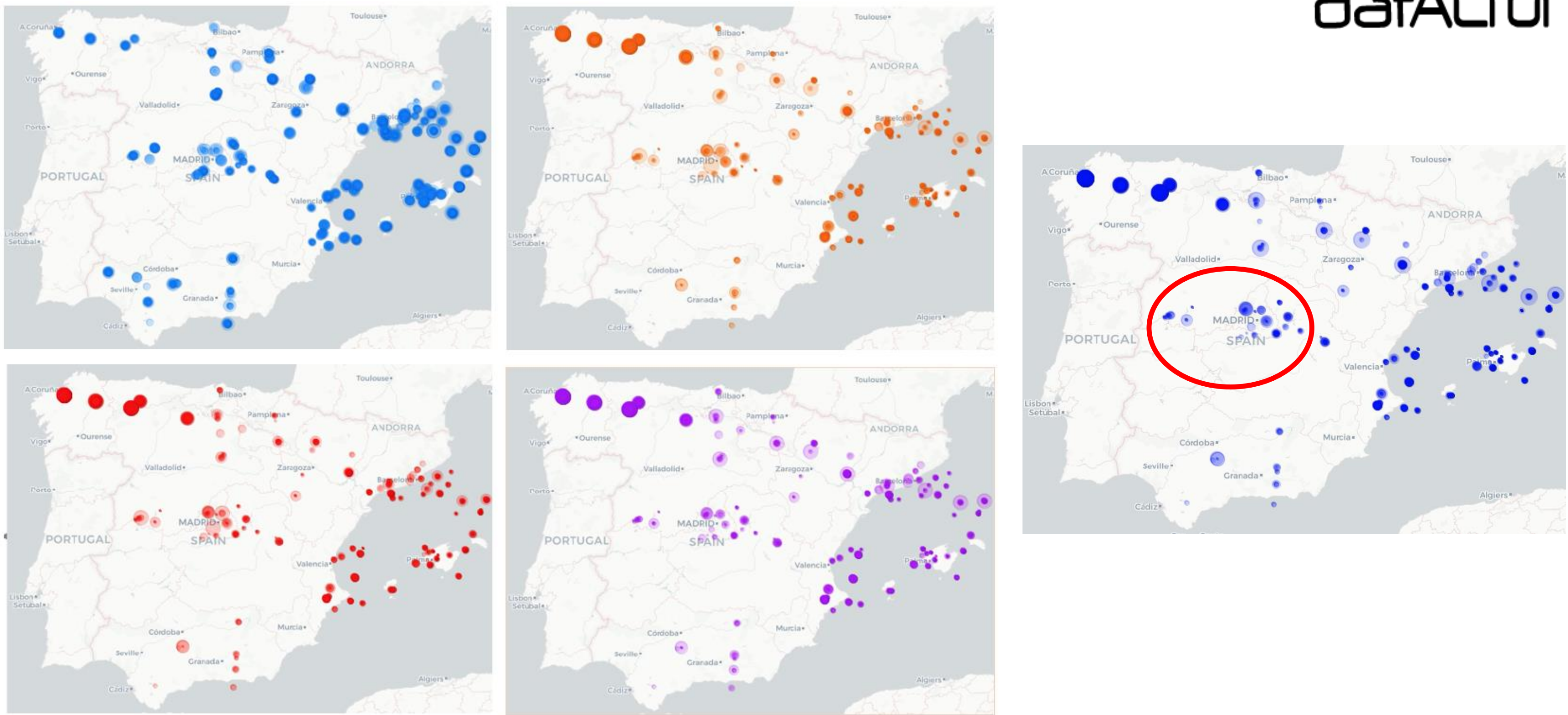






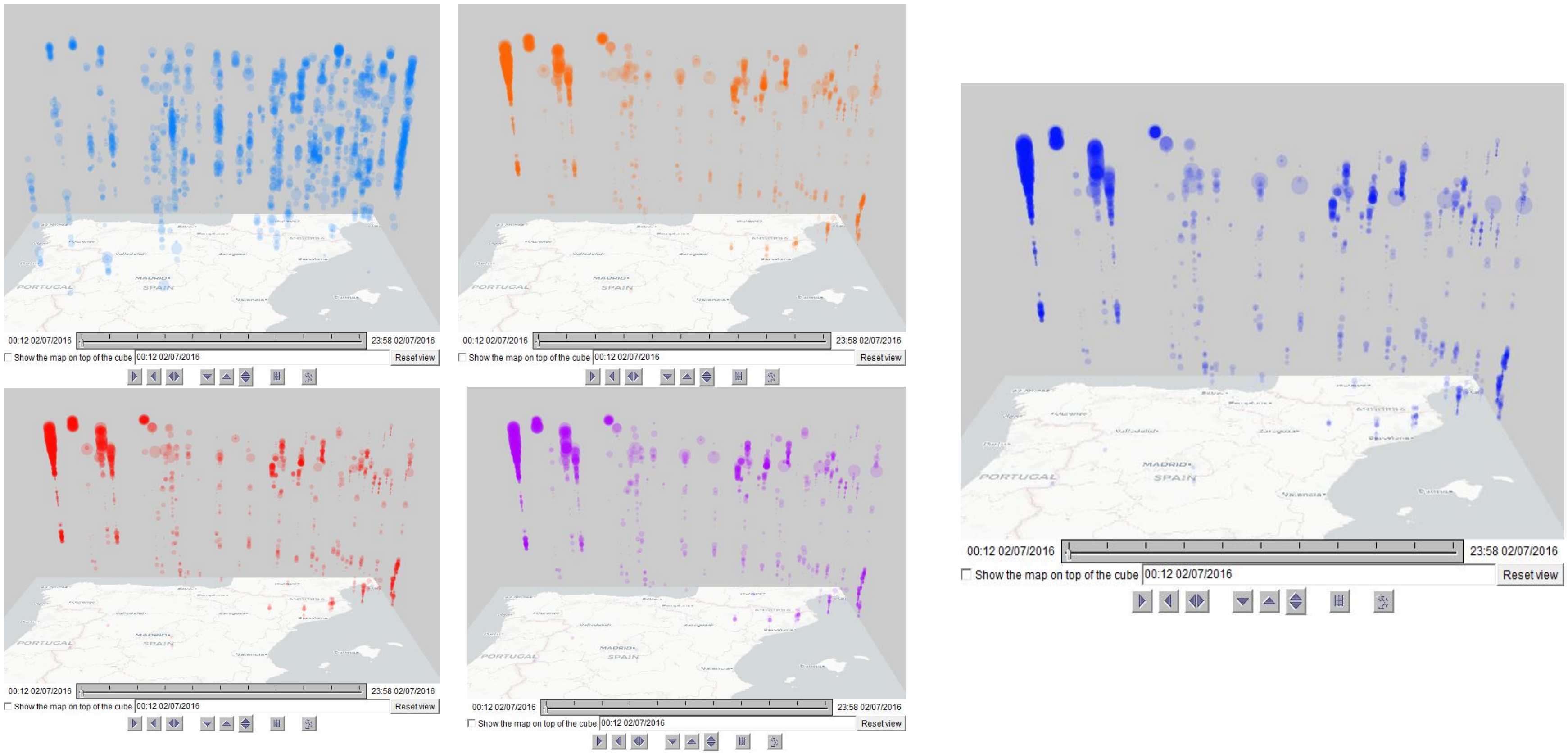
The capacity excess events are shown in a space-time cube based on the original (red) and CFMU-regulated (blue) flight data. The vertical dimension, from bottom to top, represents time.

Visualizations of solutions



Flight delays are represented by circles positioned at the sector centroids.
The sizes are proportional to the delay durations.
From top to bottom and from left to right: CFMU, AgentBased, Hierarchical, IndLearners, EdgeBased.

Visualizations of solutions

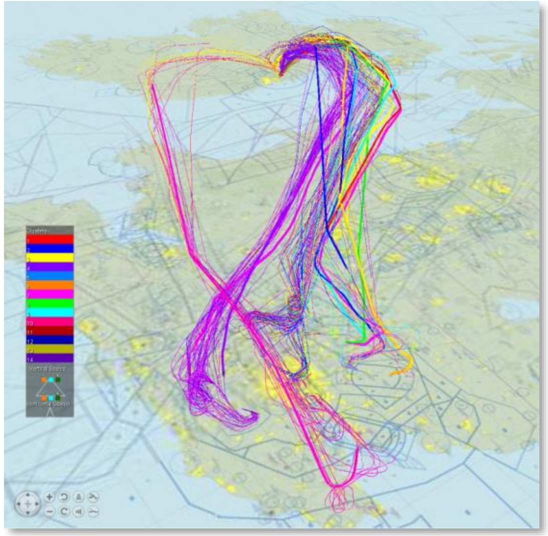


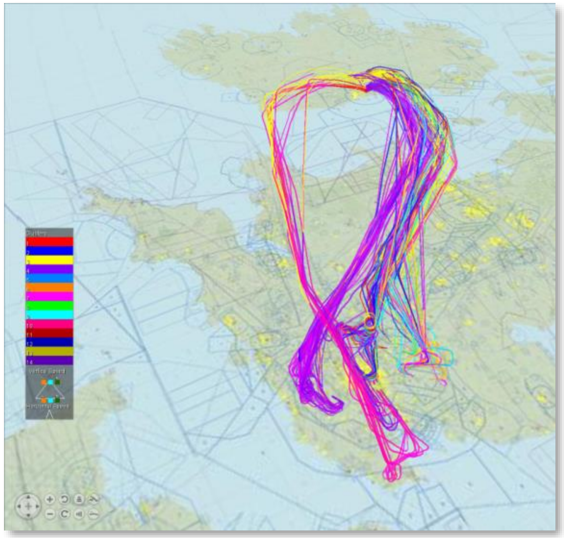
The space-time cubes show the spatio-temporal distribution of the delays. The time axis is oriented upwards. From top to bottom and from left to right: CFMU, AgentBased, Hierarchical, IndLearners, EdgeBased.

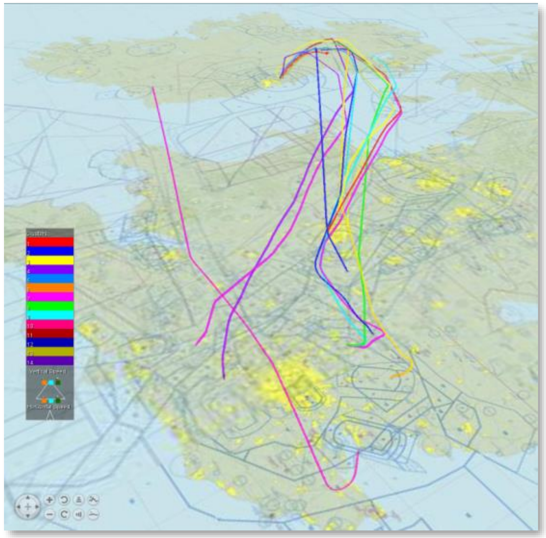
Visually supported Trajectory Comparison

Why compare flight trajectories?

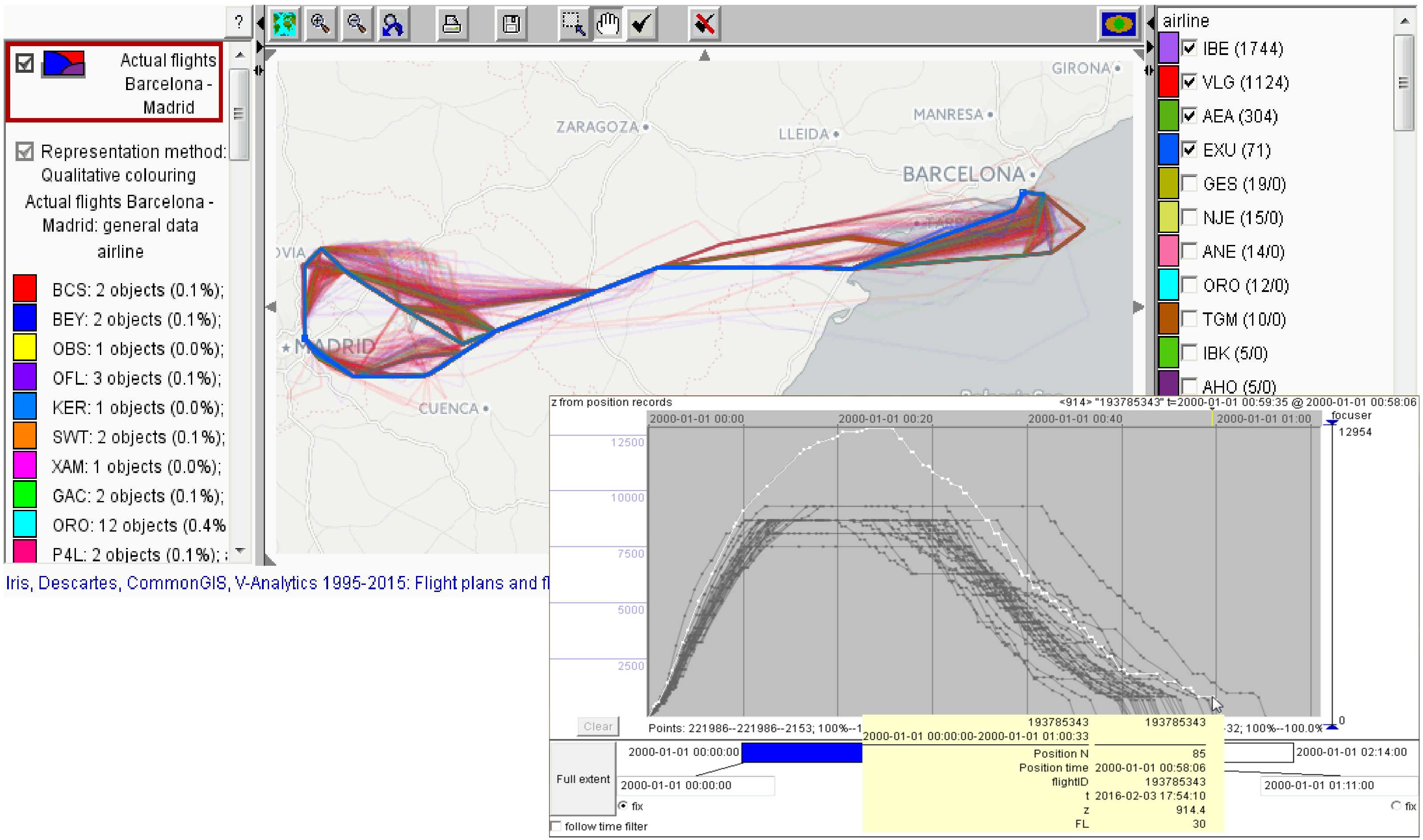
- Flight plan vs. actual flight trajectory
- Two versions of flight plan
- Actual trajectory vs. a **typical trajectory** of a given flight / representative of a cluster
- Actual trajectory vs. **predicted** trajectory
- …







Visually supported Trajectory Comparison



Visually supported Trajectory Comparison

Key ingredient: Computing and visualizing pairwise distances

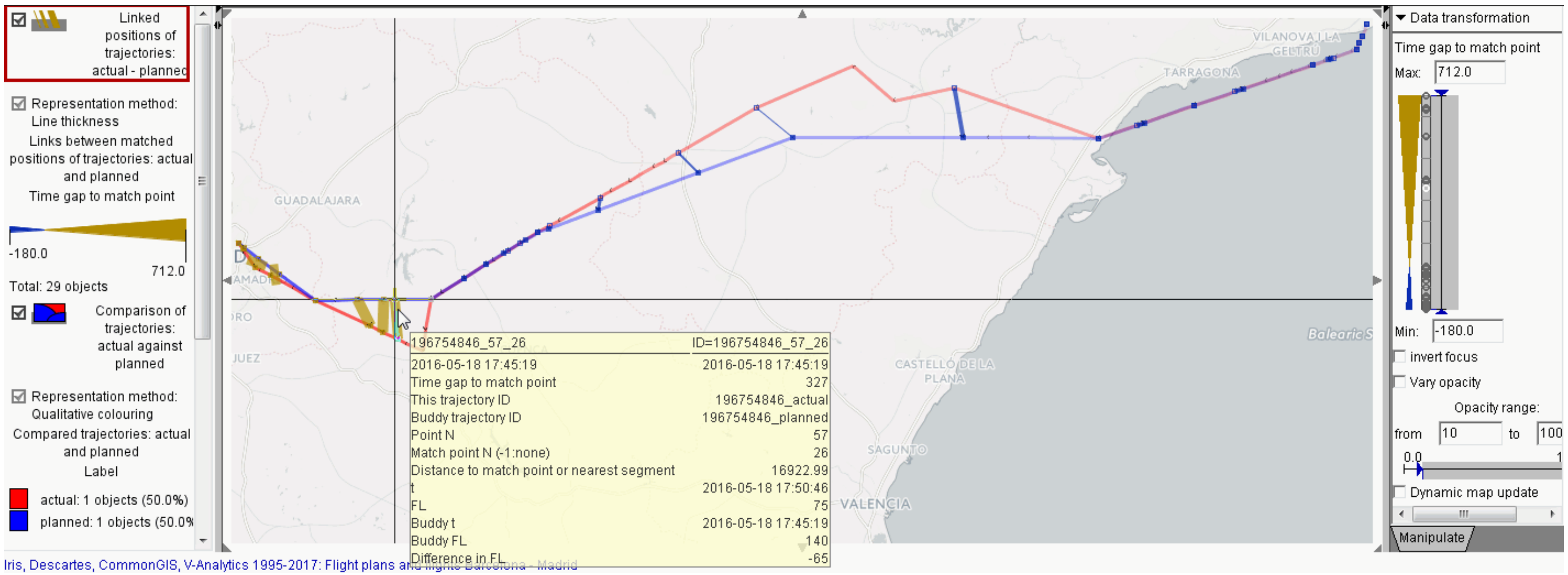
Description of the algorithm:

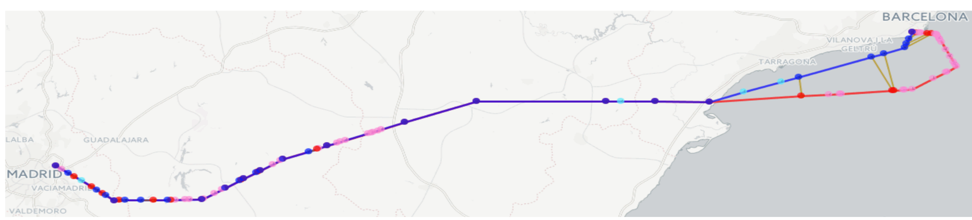
```
let M = <(1,1)>;                                          /* list M contains the pair (1,1) */
let i = 2; let j = 2;
while i <= P.length and j <= Q.length do                  /* scan the trajectories from the start to the end */
   let cp = next_candidate_pair (P, Q, M, i, j);          /* account for different inter-point distances, if needed */
   let i = cp.first; let j = cp.second;                   /* indexes of currently considered points in P and Q */
   let mi = M.lastElement[1]; let mj = M.lastElement[2];  /* indexes of the last matched points from P and Q */
   let n = argmin(distance(P[i],Q[j]), distance(P[i], Q[mj]), distance(P[mi], Q[j]), distance(P[mi], Q[mj]));
    if n = 2 and                                          /* point P[i] is a better match to point Q[mj] than P[mi] */
      distance(P[i], Q[mj]) < distance(P[i], Q[j+1])      /* point P[i] does not match Q[j+1] better than Q[mj] */
    then
        let M = M – (mi, mj) + (i, mj);                   /* replace the pair (mi, mj) in M by (i, mj) */
        let i=i+1;                                        /* proceed to the next point in P */
    end_if;
    else
       if n = 3 and                                       /* point Q[j] is a better match to point P[mi] than Q[mj] */
         distance(P[mi], Q[j]) < distance(P[i+1], Q[j])   /* point Q[j] does not match P[i+1] better than P[mi] */
       then
           let M = M – (mi, mj) + (mi, j);                /* replace the pair (mi, mj) in M by (mi, j) */
           let j = j +1;                                  /* proceed to the next point in Q */
       end_if;
       else
          let n = argmin(distance(P[i],Q[j]), distance(P[i], Q[j+1]), distance(P[i+1], Q[j]));
          if n = 2 and                                    /* point Q[j+1] is a better match to point P[i] than Q[j] */
            distance(P[i], Q[j+1]) < distance(P[i+1], Q[j+1])  /* point Q[j+1] is not a better match to P[i+1] than to P[i] */
          then
              let j = j +1;                               /* proceed to the next point in Q */
          end_if;
          else
             if n = 3 and                                 /* point P[i+1] is a better match to point Q[j] than P[i] */
               distance(P[i+1], Q[j]) < distance(P[i+1], Q[j+1])  /* point P[i+1] is not a better match to Q[j+1] than to Q[j] */
             then
                 let i = i +1;                            /* proceed to the next point in P */
             end_if;
             else
                 let M = M + (i,j);                       /* add the pair (i, j) to M */
                 let i = i +1; let j = j +1;              /* proceed to the next points in P and Q */
             end_else;
          end_else;
       end_else;
    end_else;
end_while;
return M;
```

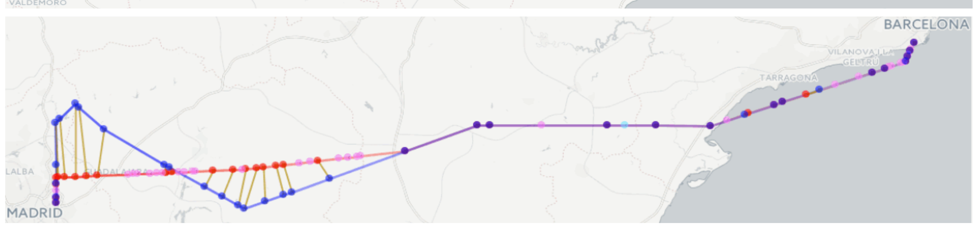
```
function next_candidate_pair (P, Q, M, i, j):
if i > P.length or j > Q.length return null;
let mi = M.lastElement[1]; let mj = M.lastElement[2];     /* (mi, mj) is the last matched pair */
let d1 = distance(P[i], P[mi]); let d2 = distance(Q[j], Q[mj]);   /* inter-point distances in P and Q */
if d1 > d2 then
     while d1 > d2 * TT and j < Q.length do               /* much larger inter-point gap in P */
          let j = j+1; let d2 = distance(Q[j], Q[mj]);    /* proceed to the next point in Q */
     end_while;
end_if;
else
     while d2 > d1 * TT and i < P.length do               /* much larger inter-point gap in Q */
          let i = i+1; let d1 = distance(P[i], P[mi]);    /* proceed to the next point in P */
     end_while;
end_else;
return (i, j);
```

WP2: Single Trajectory Prediction

D2.2 Visually supported Trajectory Comparison

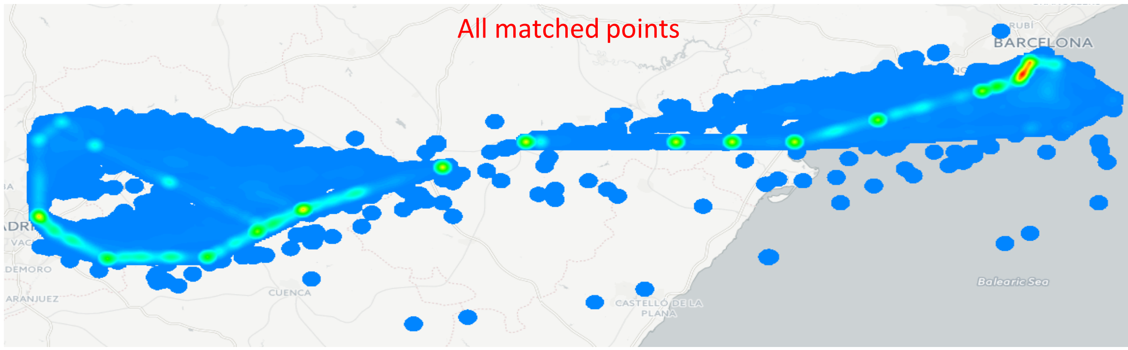


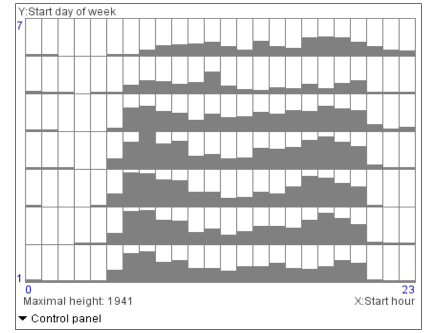


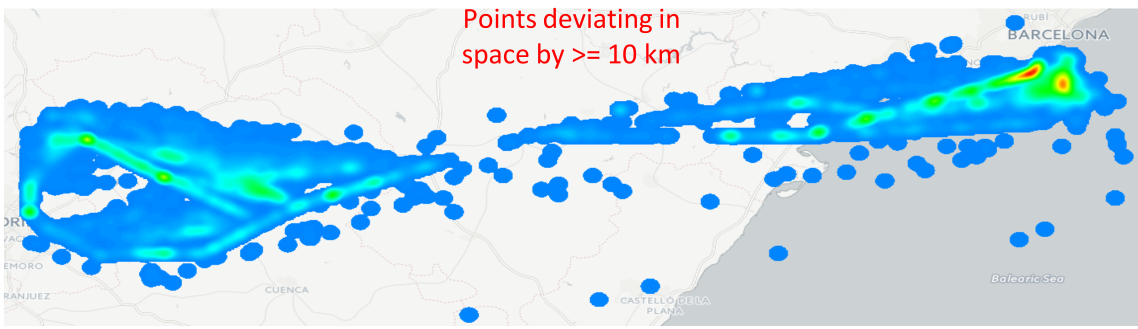


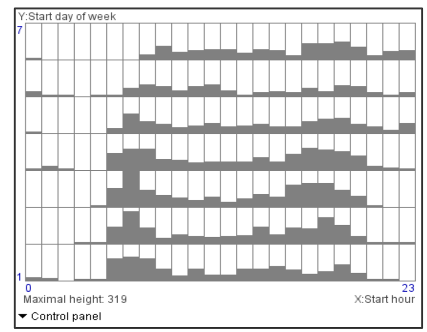
WP2: Single Trajectory Prediction

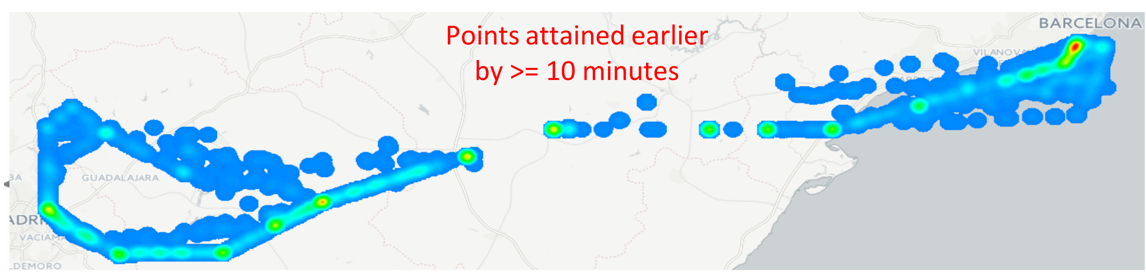
D2.2 Visually supported Trajectory Comparison

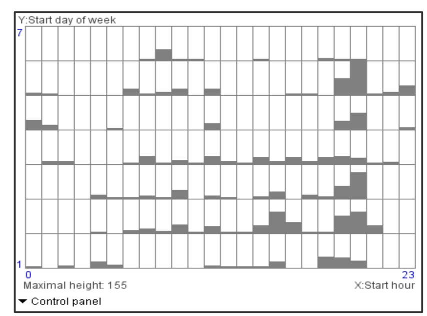












Case Study I – Approach Route Analysis

This project has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No [number]

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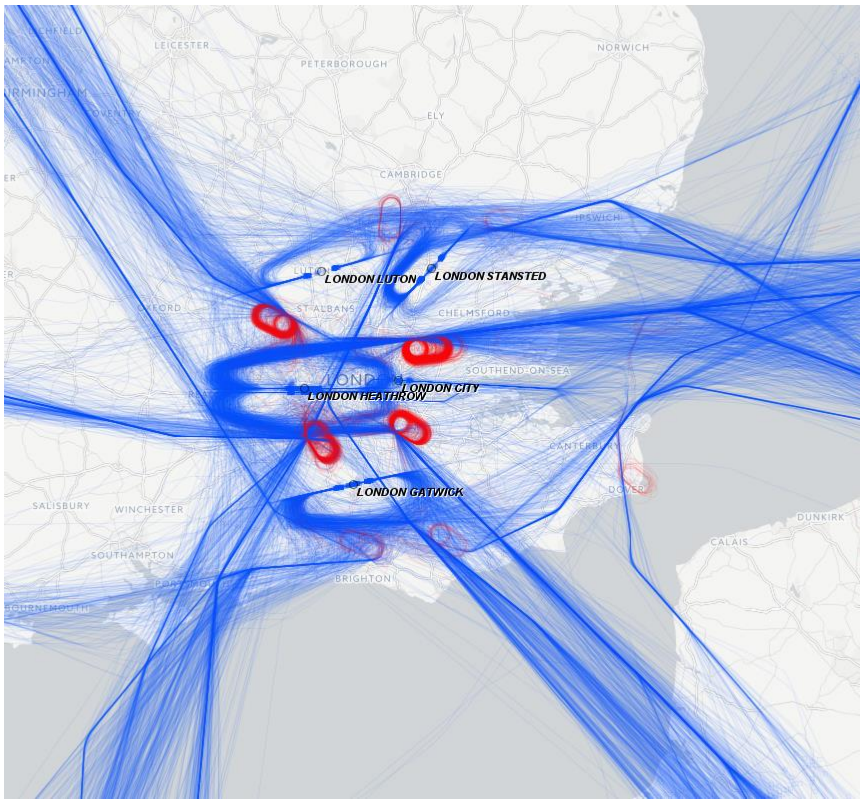
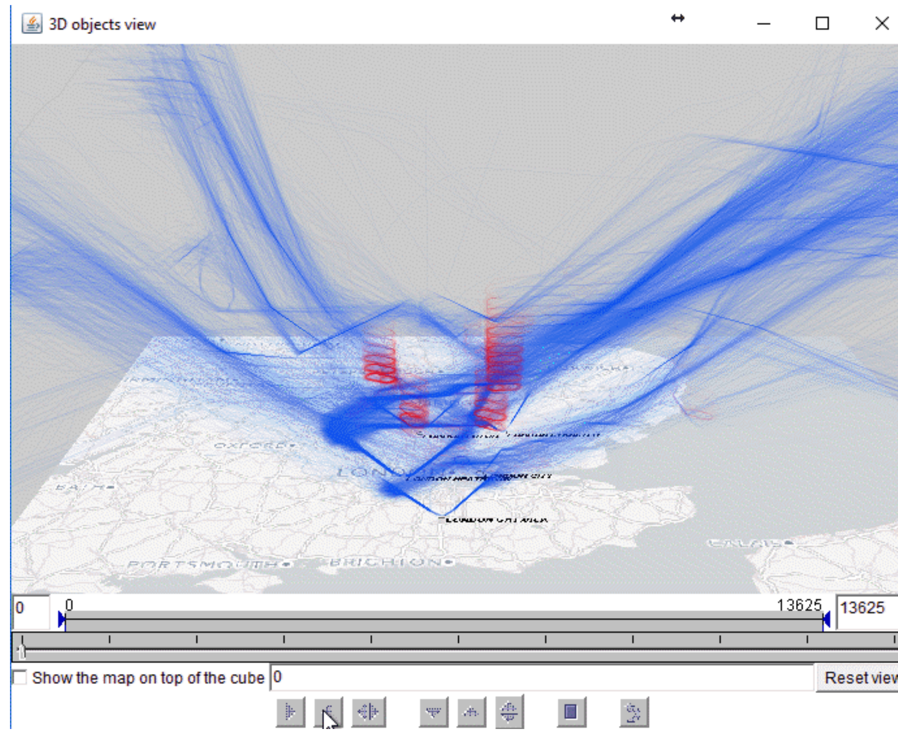
Task: Extract the airport approach routes and observe the wind impact

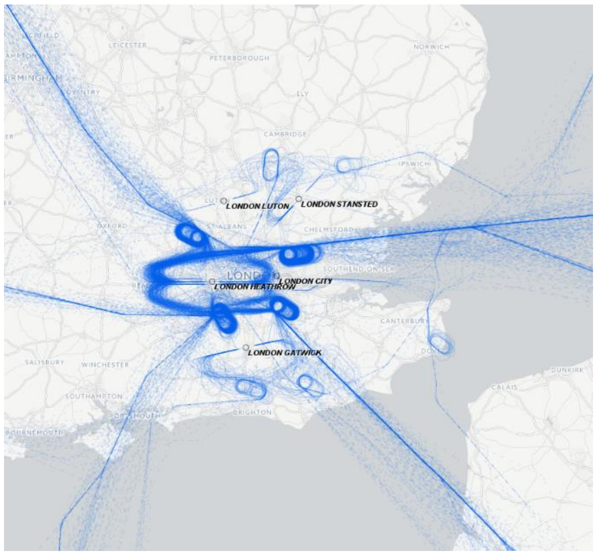




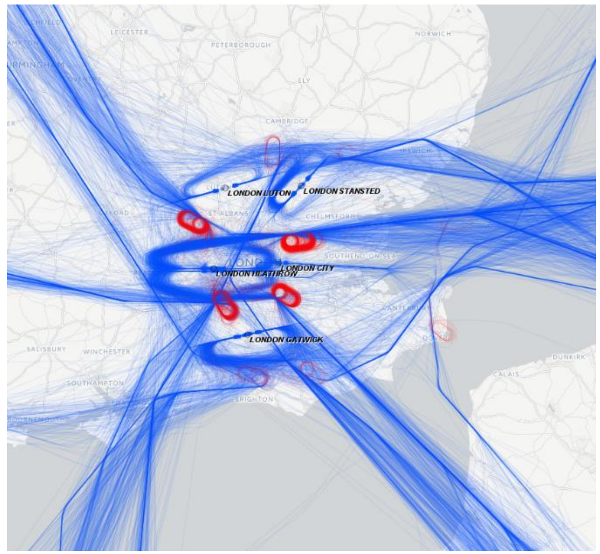
Challenge: The holding loops are <u>not</u> essential parts of the approach routes

Visual support to interactive filtering

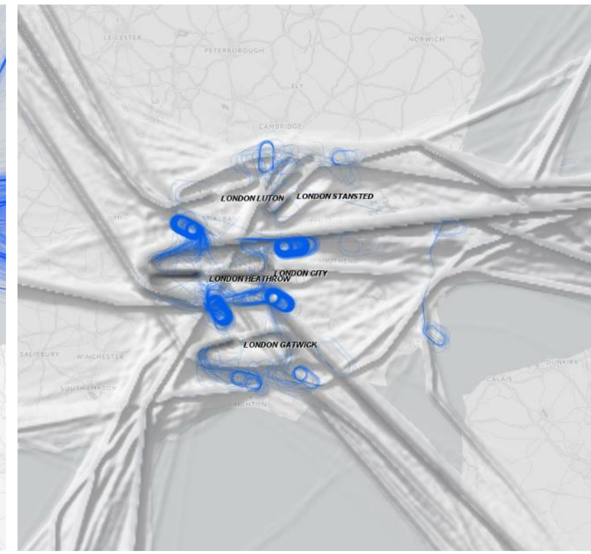
Workflow: *filter* → *cluster* → *summarize* → *analyse*



Filter-aware rendering



Filtering →
Boolean attribute → visual encoding



Different level of detail for active and inactive parts

Progressive clustering

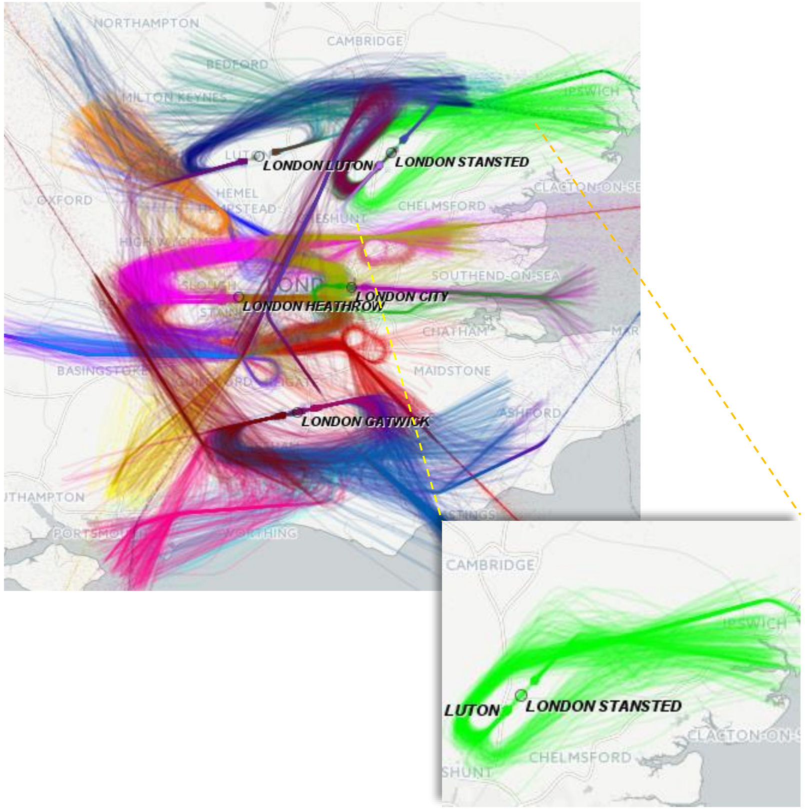
Workflow: *filter* → *cluster* → *summarize* → *analyse*

Application of clustering with different distance functions or parameter settings to different data subsets

- Particularly, subsets may be defined by previous clustering runs

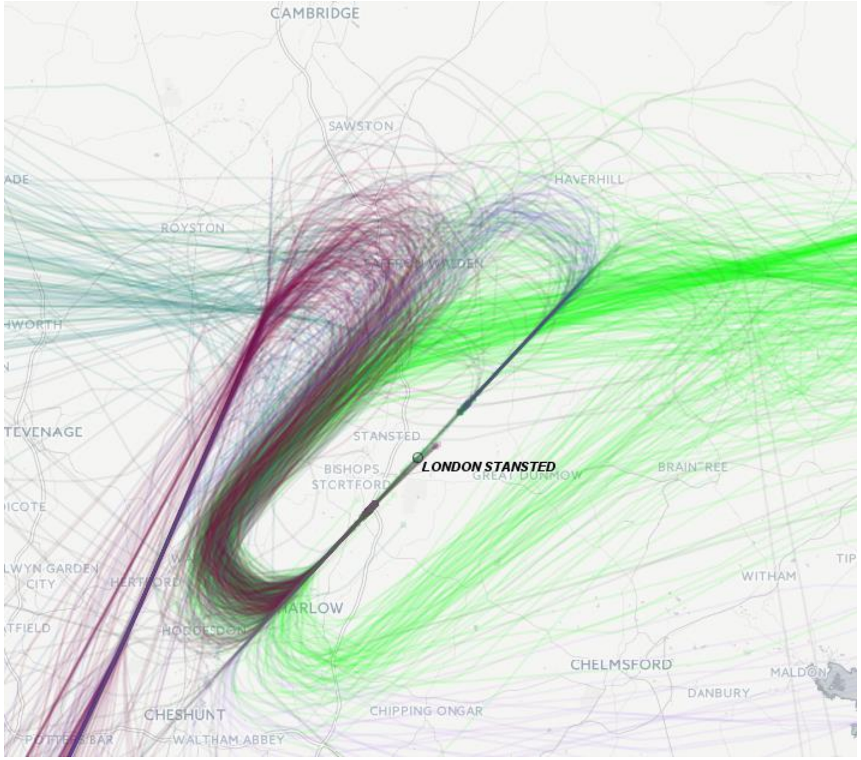
Useful when clustering of the whole set produces clusters of differing quality

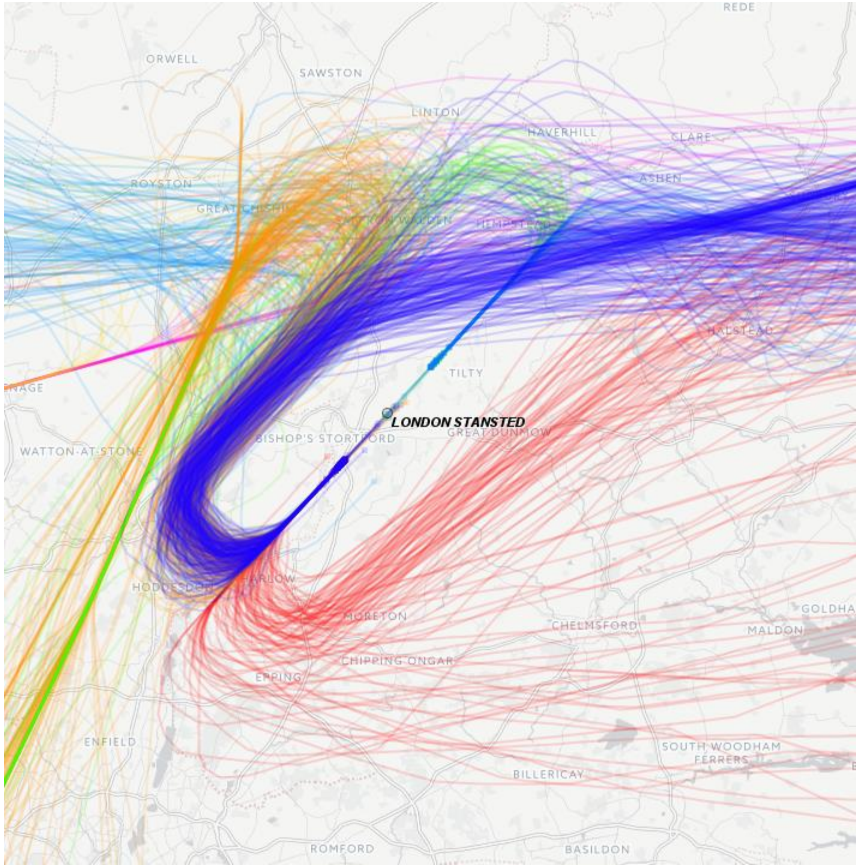
- "Bad" clusters (with high internal variation) can be refined through further clustering and good clusters can be preserved

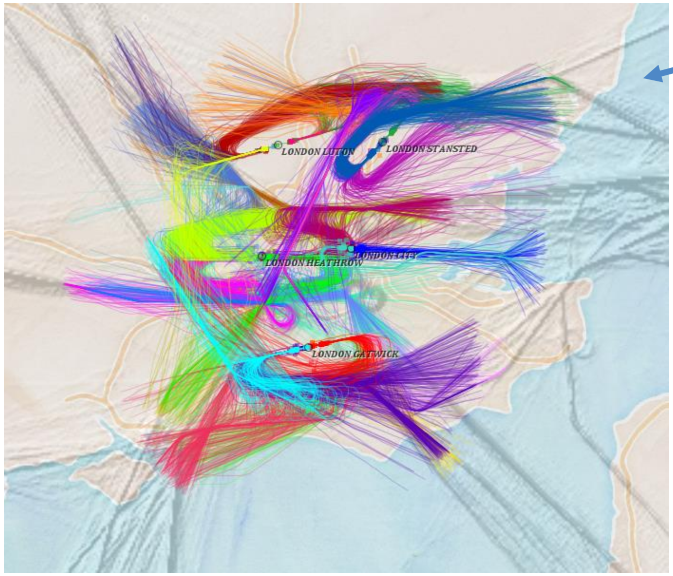


An example of cluster refinement

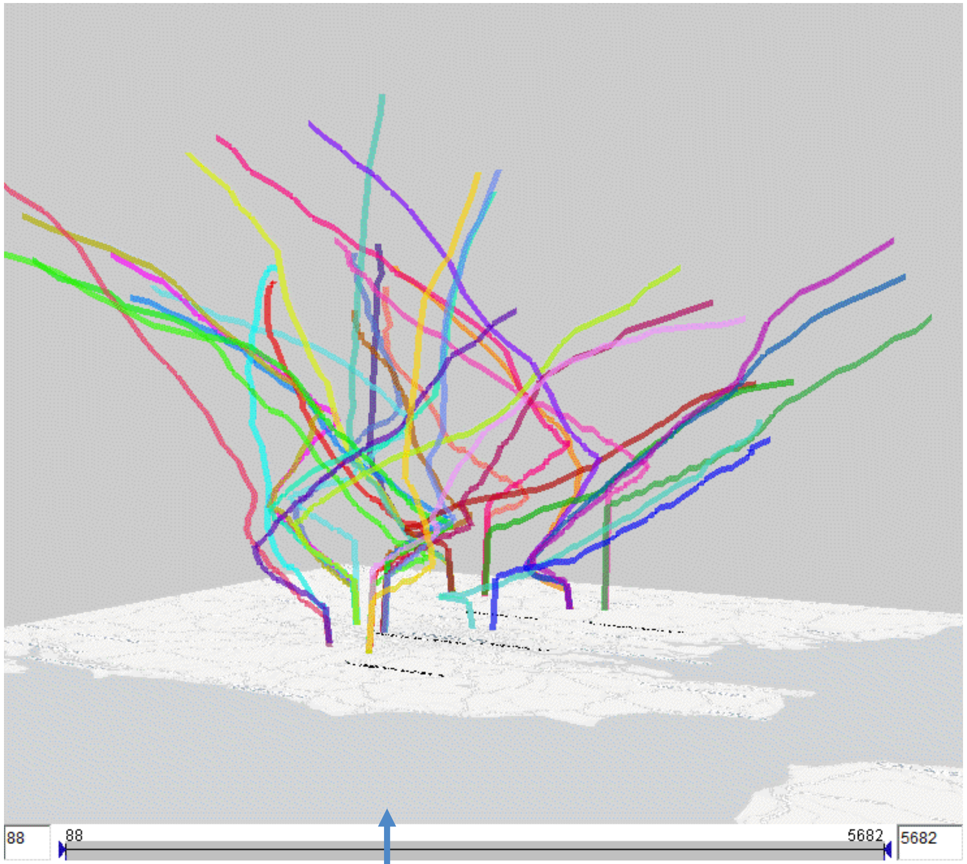
Workflow: *filter* → *cluster* → *summarize* → *analyse*

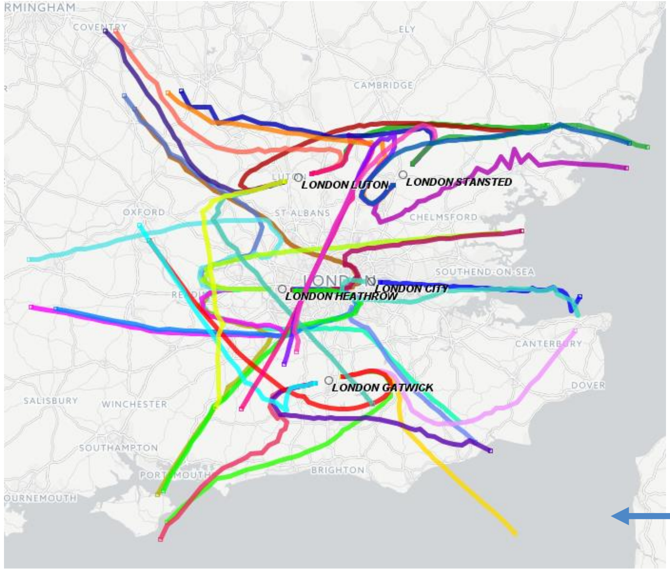






Resulting clusters by approach routes (loops disregarded)





Central trajectories of the clusters represent the routes.

Loop statistics by the routes

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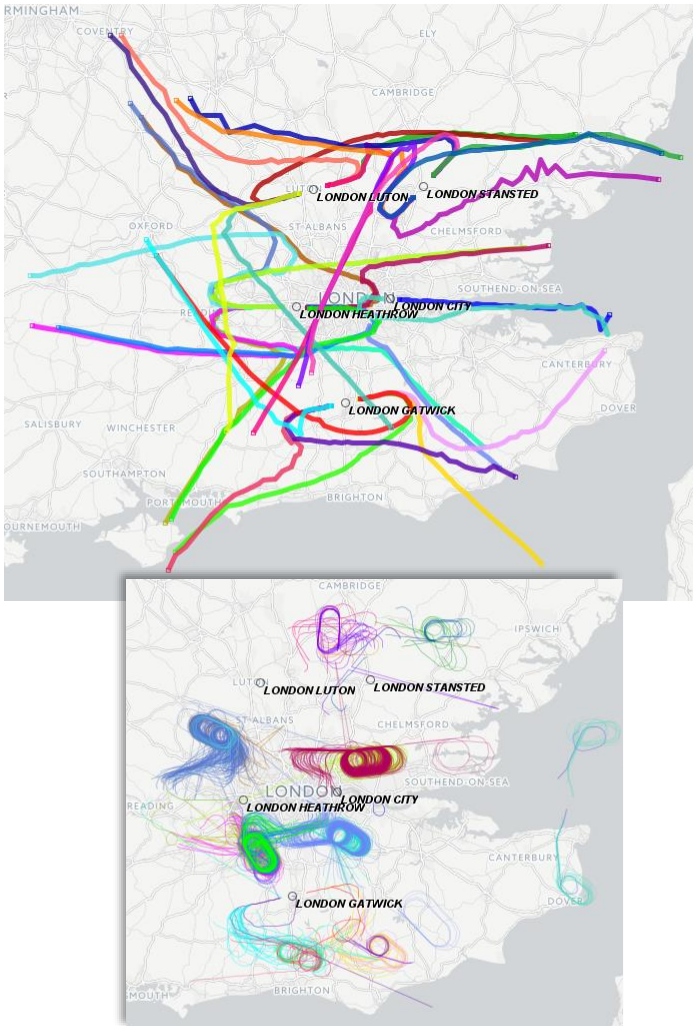
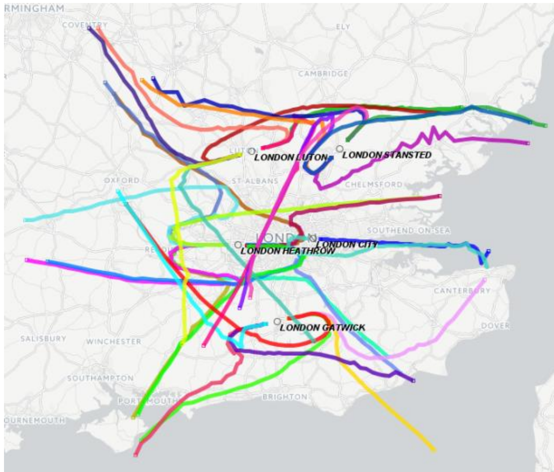
Workflow: *filter* → *cluster* → *summarize* → *analyse*

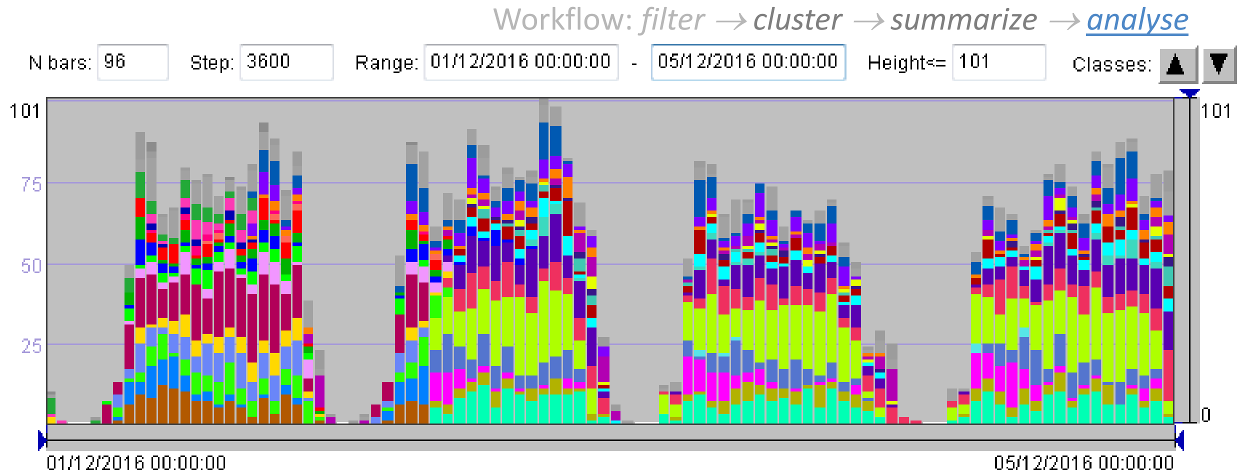


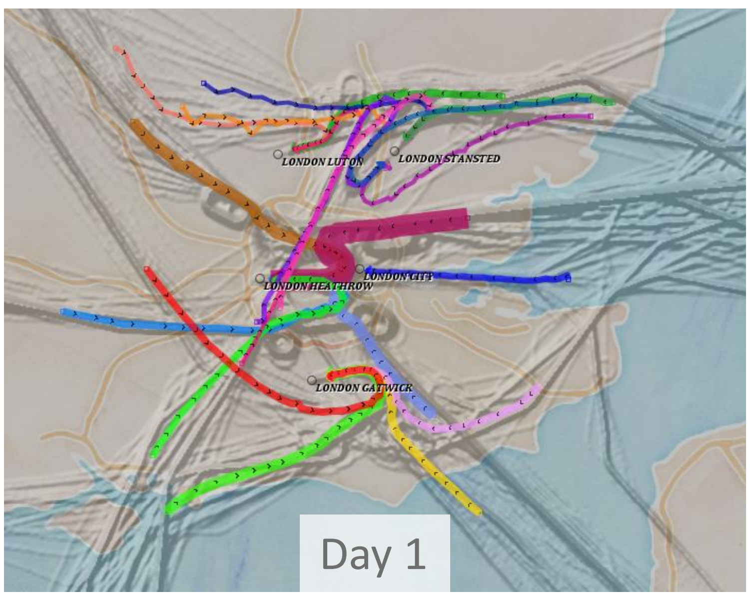
	N members	N trajectories with loops	% trajectories with loops	Loop duration (minutes), sum	Loop duration (minutes), mean	Loop duration (minutes), std.dev.	Loop duration (minutes), min	Loop duration (minutes), q1	Loop duration (minutes), median	Loop duration (minutes), q3	Loop duration (minutes), max
2/2	99										
29/1	36										
27/1	36										
26/1	11										
25/1	32										
6/1	258	184	71.3	1892.10	10.283	4.4243	2.02	7.03	8.78	12.72	29.15
3/1	152	91	59.9	784.30	8.619	3.7594	2.68	5.82	8.27	11.02	19.95
2/1	137	80	58.4	644.92	8.061	3.4982	2.78	5.33	7.14	10.80	17.67
17/1	59	34	57.6	336.40	9.894	4.0622	3.15	7.04	9.22	12.64	17.18
5/1	89	50	56.2	402.63	8.053	3.6846	3.17	6.00	6.75	10.83	17.90
1/1	342	177	51.8	1340.78	7.575	4.1491	1.78	4.25	6.37	9.97	19.25
12/1	141	71	50.4	764.42	10.766	4.8091	4.77	7.55	9.28	12.87	25.67
8/1	746	374	50.1	2534.43	6.777	3.6097	2.52	3.86	4.97	9.34	19.07
28/1	12	6	50.0	42.42	7.069	2.7334	4.58	4.73	5.63	10.85	10.97
7/1	10	5	50.0	46.17	9.233	2.2277	7.15	7.33	8.07	11.72	13.08
14/1	314	136	43.3	1247.33	9.172	4.5198	3.13	4.30	9.18	12.63	22.63
19/1	35	15	42.9	132.80	8.853	2.3794	4.92	7.13	8.20	12.00	13.02
4/1	164	60	36.6	510.07	8.501	2.7680	2.95	6.55	8.71	10.25	19.32
22/1	113	23	20.4	128.00	5.565	1.9633	1.52	4.67	5.15	5.83	10.32
13/1	84	14	16.7	109.05	7.789	2.2688	4.90	6.38	7.16	8.08	13.07
15/1	75	8	10.7	74.67	9.333	2.4880	3.82	8.14	9.82	11.24	12.52
1/3	54	5	9.3	32.90	6.580	0.8281	5.28	5.77	6.57	7.40	7.78
5/2	179	16	8.9	110.05	6.878	0.8754	5.37	6.07	6.73	7.80	8.10
3/2	13	1	7.7	6.78	6.783	0.0000	6.78	6.78	6.78	6.78	6.78
10/1	123	7	5.7	52.02	7.431	2.1660	5.38	5.67	6.13	8.63	11.90
21/1	64	3	4.7	23.10	7.700	2.1741	4.70	4.70	8.62	9.78	9.78
18/1	69	3	4.3	17.48	5.828	1.8367	3.23	3.23	7.02	7.23	7.23
11/1	306	13	4.2	87.80	6.754	1.7163	4.23	5.02	6.75	8.47	9.60
2/3	201	8	4.0	41.38	5.173	0.8310	3.88	4.50	5.13	5.97	6.37
4/2	83	3	3.6	20.87	6.956	1.8968	4.47	4.47	7.33	9.07	9.07
20/1	62	2	3.2	12.78	6.392	0.1250	6.27	6.27	6.39	6.52	6.52
6/2	33	1	3.0	5.67	5.667	0.0000	5.67	5.67	5.67	5.67	5.67
16/1	363	9	2.5	45.70	5.078	1.1467	3.77	4.32	4.52	6.25	7.18
23/1	133	1	0.8	4.00	4.000	0.0000	4.00	4.00	4.00	4.00	4.00

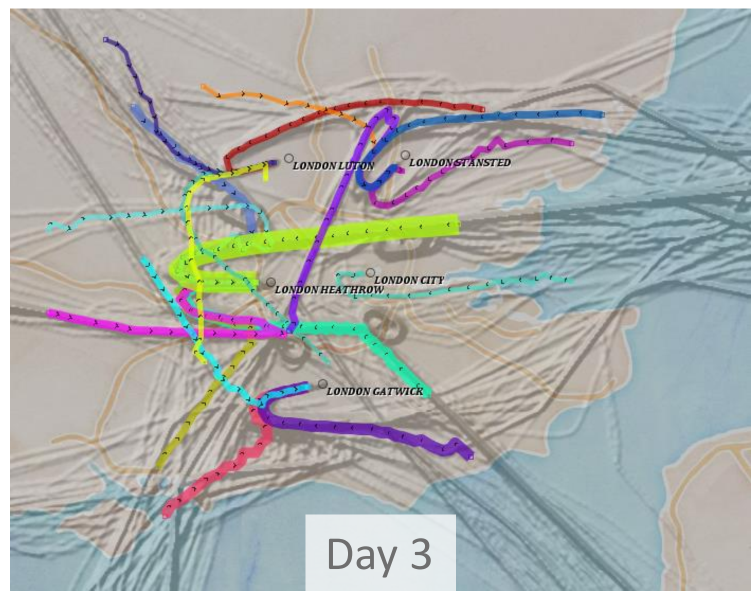
☐ group by classes Sort by: % trajectories with loops Descending ☑ TableLens ☑ condensed Attribute...

Use of the routes over time









Understanding the wind impact

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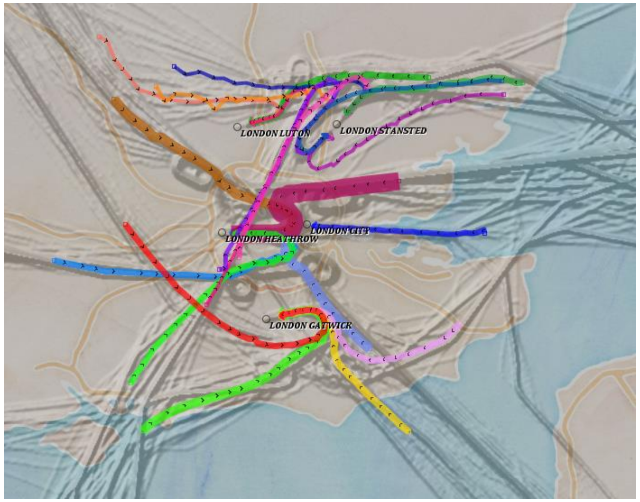
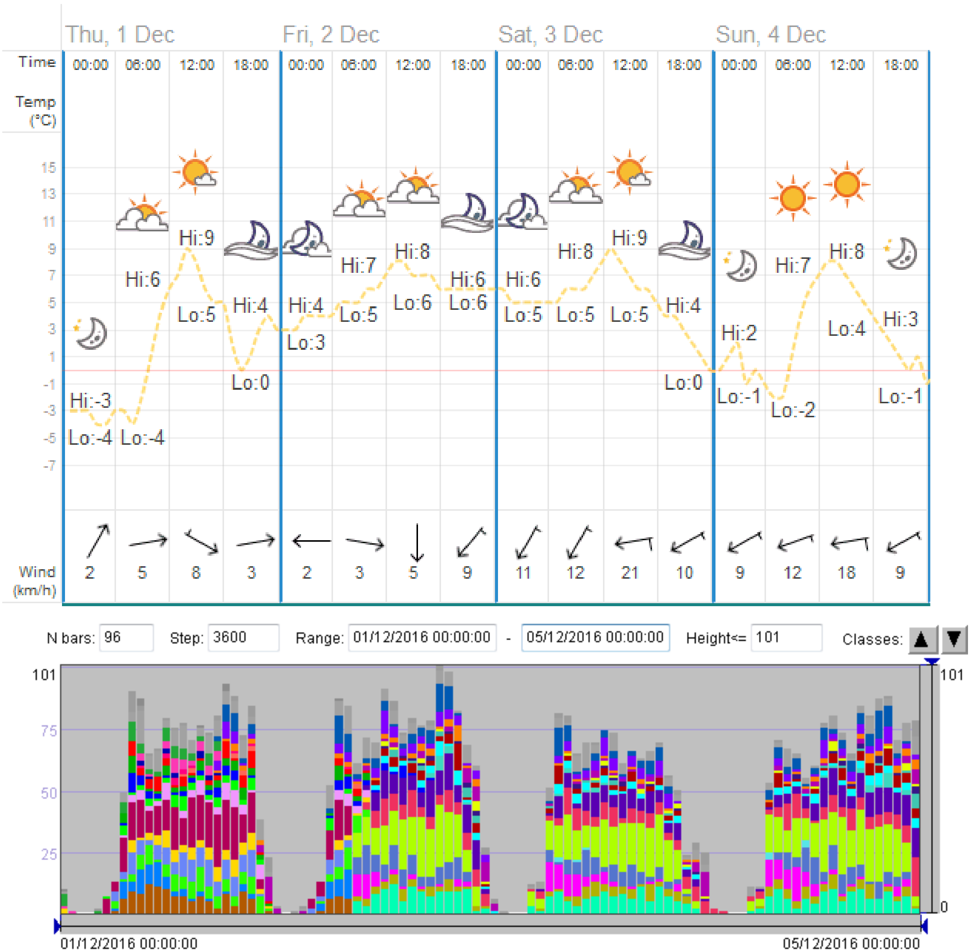
Workflow: *filter* → *cluster* → *summarize* → *analyse*



December 2016 Weather in London — Graph



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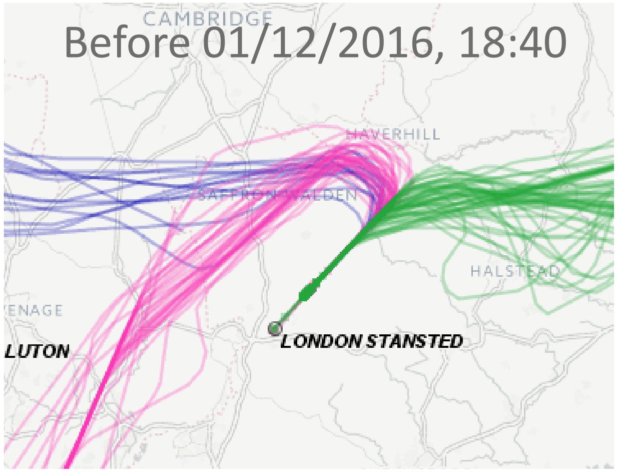
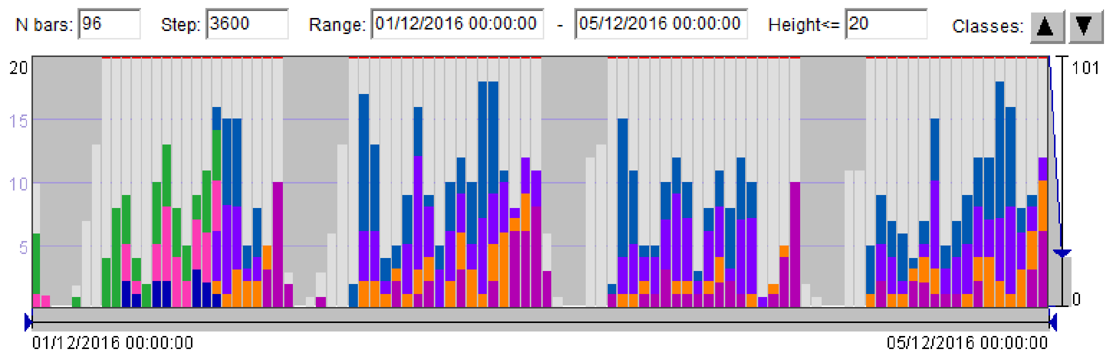
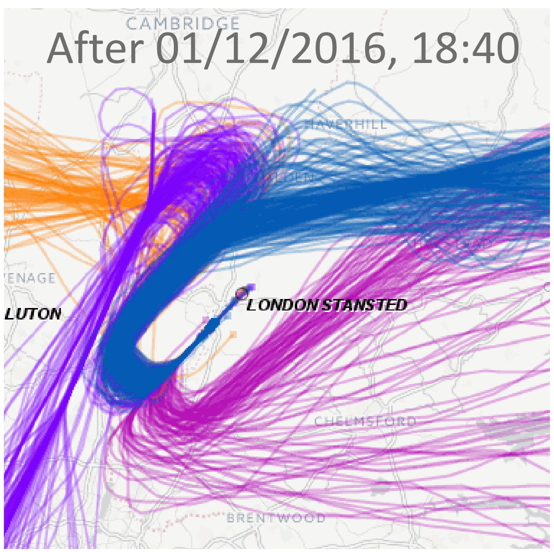
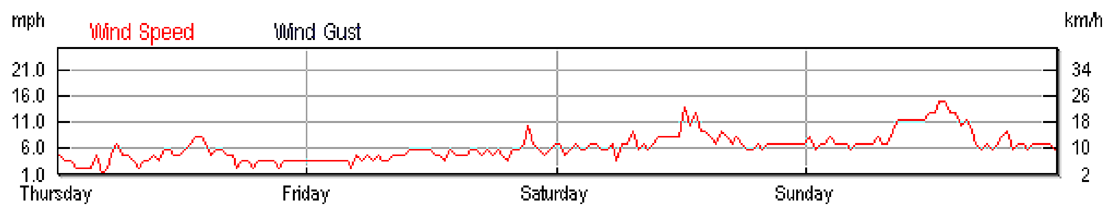
The routes to Stansted

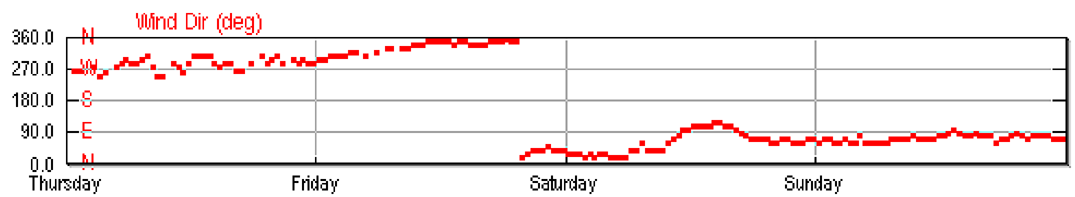
Workflow: *filter* → *cluster* → *summarize* → *analyse*







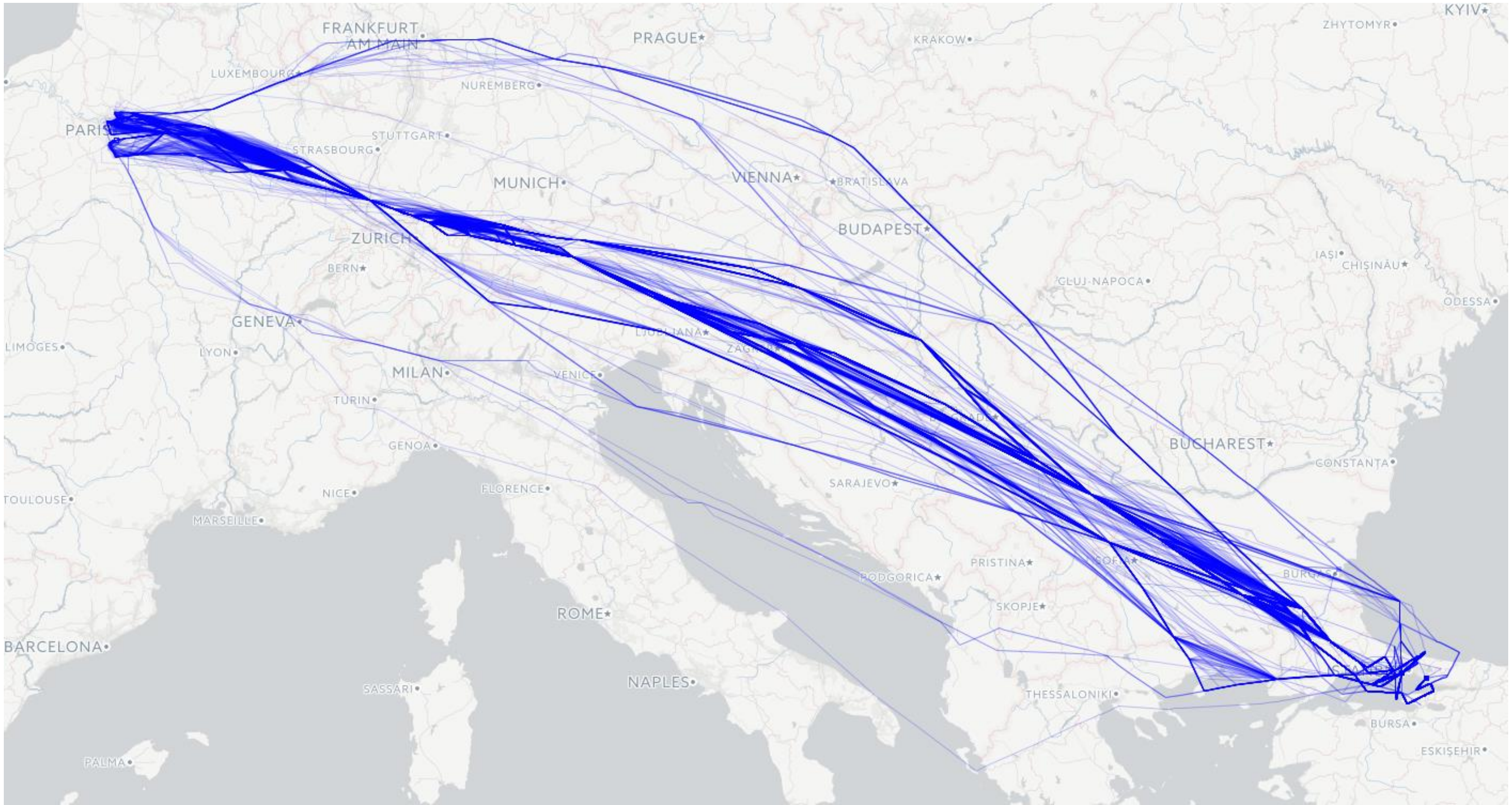




Case Study II –
Route Choice Criteria Analysis

This project has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No [number]

Task: Identify and compare the major flight routes from Paris to Istanbul



Gennady Andrienko, Natalia Andrienko, Georg Fuchs, Jose Manuel Cordero Garcia

Clustering Trajectories by Relevant Parts for Air Traffic Analysis

IEEE Transactions on Visualization and Computer Graphics
(proceedings IEEE VAST 2017), 2018, vol. **24**(1): 34-44

The movements around the airports are not parts of the routes

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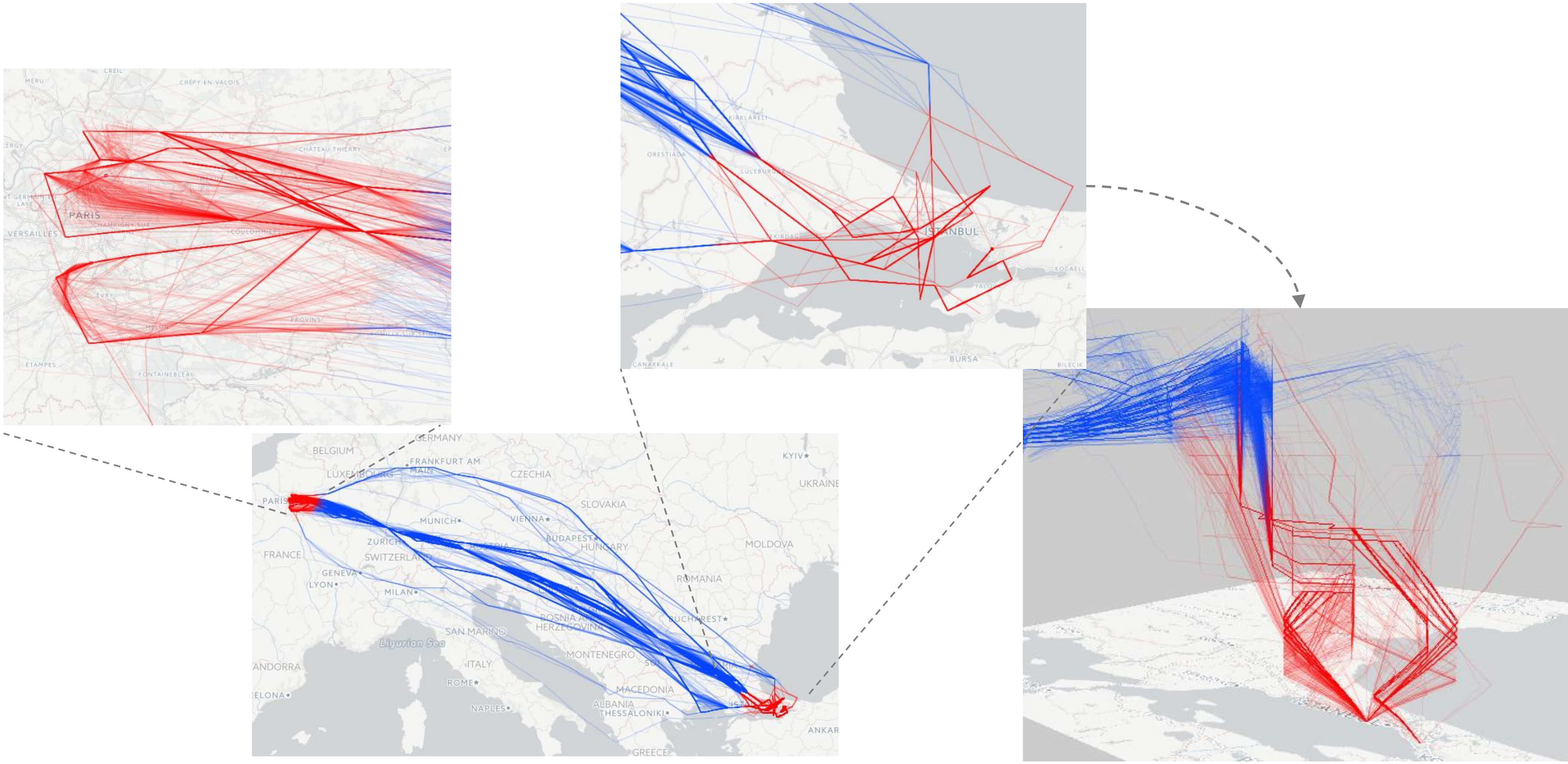
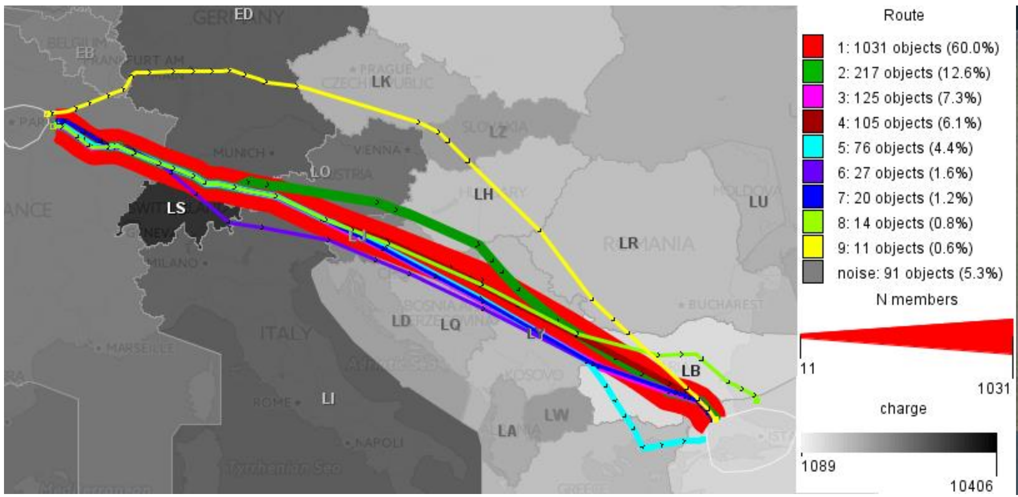
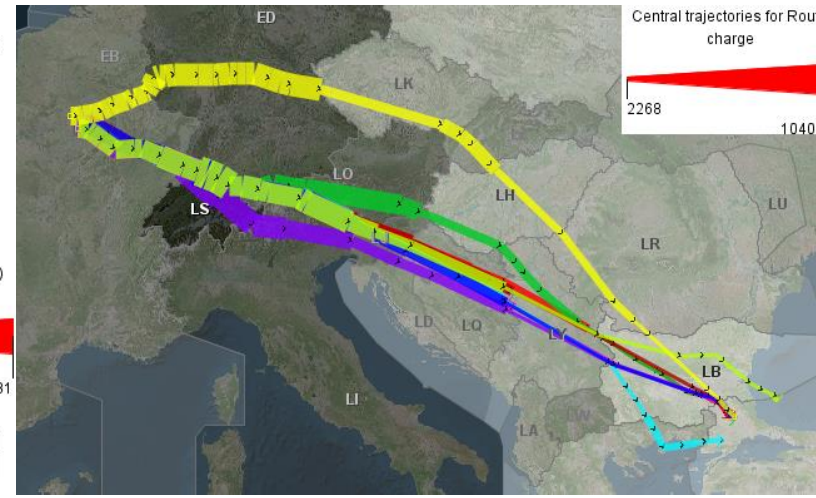


Route popularity and navigation charges

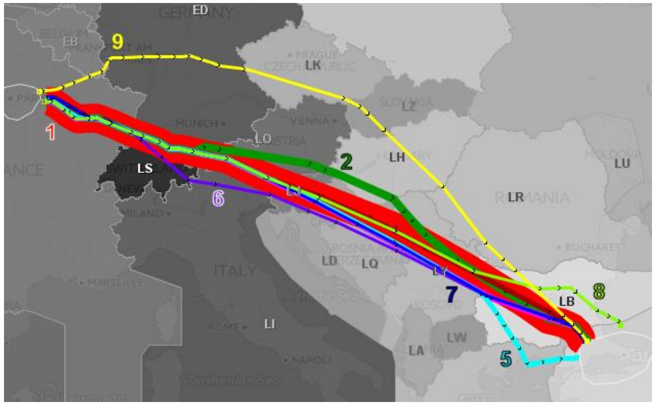


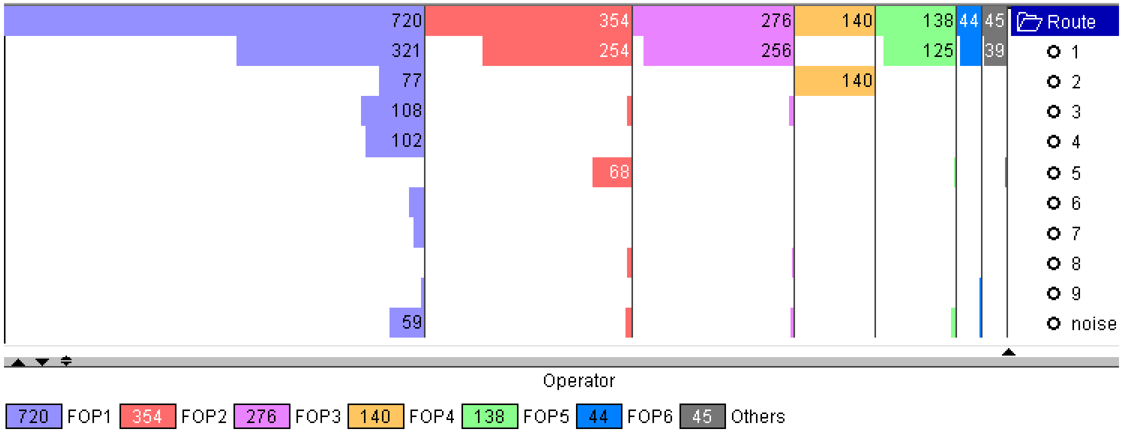


	N members	charges, min	charges, q1	charges, mean	charges, median	charges, q3	charges, max
2	217	434.9	457.8	459.10	459.4	460.2	492.8
4	105	486.4	508.1	512.67	513.8	517.0	528.2
8	14	476.6	512.4	511.43	515.5	517.2	517.5
1	1031	472.2	512.8	514.36	515.6	517.8	547.3
3	125	500.6	519.2	521.45	521.8	523.2	536.5
7	20	519.9	521.3	522.90	522.2	523.0	535.9
5	76	509.7	533.7	539.24	540.3	542.7	573.1
noise	91	454.2	510.0	565.12	544.6	650.0	745.8
9	11	609.3	609.4	610.60	609.6	612.5	614.2
6	27	646.6	654.2	655.47	655.7	656.4	660.3

☐ group by classes Sort by: charges, median Ascending ☑ TableLens ☑ condensed Attribute...

Route choices





	N members	charges, min	charges, q1	charges, mean	charges, median	charges, q3	charges, max
2	217	434.9	457.8	459.10	459.4	460.2	492.8
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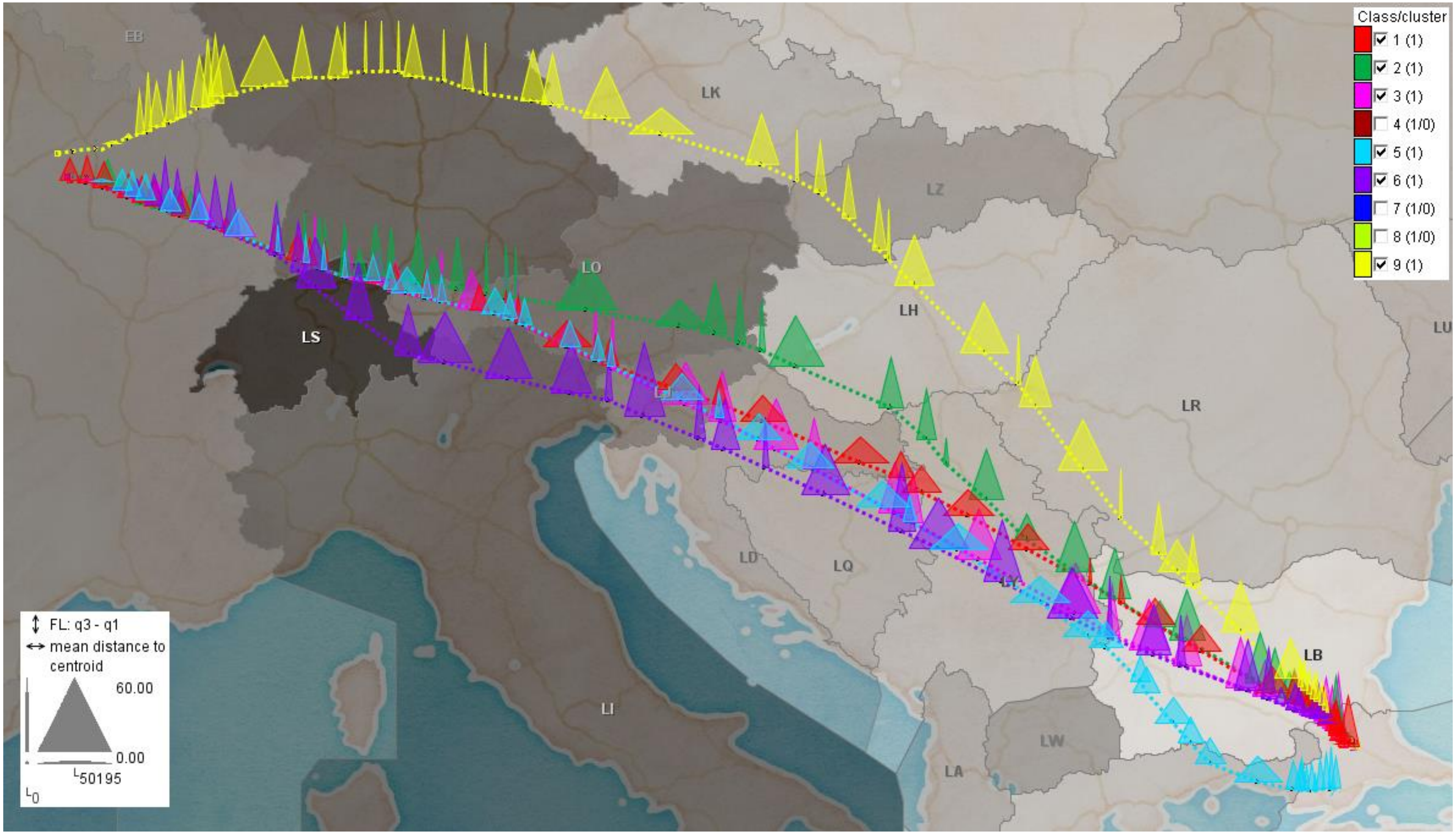
6	27	646.6	654.2	655.47	655.7	656.4	660.3

group by classes Sort by: charges, median Ascending TableLens condensed Attribute...

	N members	length, min	length, q1	length, mean	length, median	length, q3	length, max
5	76	1242.0	1255.3	1269.17	1268.5	1276.3	1321.2
8	14	1253.3	1261.6	1272.19	1272.8	1283.5	1287.2
7	20	1268.5	1272.0	1278.83	1274.9	1282.2	1301.7
1	1031	1186.8	1273.9	1285.59	1288.6	1294.1	1315.8
3	125	1266.8	1275.0	1285.89	1288.9	1294.1	1317.7
4	105	1225.5	1272.9	1285.30	1289.9	1294.0	1310.8
noise	91	1243.1	1280.2	1304.96	1295.4	1320.4	1409.2
6	27	1271.6	1283.5	1294.62	1296.7	1302.6	1315.2
2	217	1243.9	1286.0	1296.40	1300.4	1304.8	1325.0
9	11	1338.2	1340.8	1349.56	1349.0	1352.9	1377.3

group by classes Sort by: length, median Ascending TableLens condensed Attribute...

Route variability



Conclusions

Visual Analytics – human expert in the loop

„Detect the expected, discover the unexpected“

- Data Exploration & Understanding (raw data)
- Pattern Extraction & Feature Engineering (refined data)
- Visual exploration of modeling results
- „What-if“ Analyses

Application to the ATM domain @ DART, datAcron

- Complex data (4D trajectories; weather, airspace design, … contextual data)
- Complex algorithms in moving towards TBO
- Decision support (vs. autonomous „black box“ decision making)

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Thank you very much for your attention!

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