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ELSA Air Traffic Simulator: an Empirically grounded Agent Based Model for the SESAR scenario

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work done in collaboration with:

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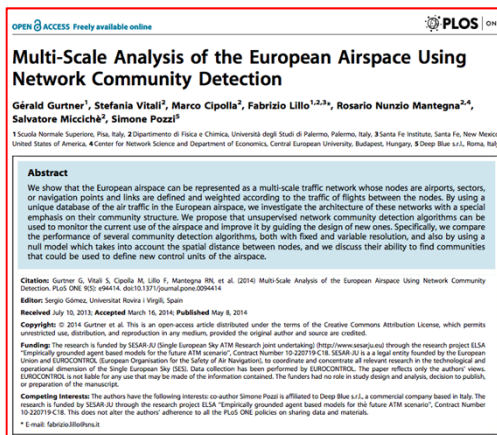
within the research project:

ELSA: Empirically grounded Agent Based Model for the future Air Traffic Management scenario - EXTENSION

<http://complexworld.eu/wiki/ELSA>



<http://www.sesarju.eu/newsroom/all-news/mastering-complexity-tomorrow-atm-system>



Investigating a relevant socio-technical complex system with tools and methodologies of Statistical Physics, Network Science and Complex Systems.

How the system works

STRATEGIC PHASE: planning of the trajectories

Accommodate as many as possible aircraft in a certain airspace, given the sectors capacity constraints

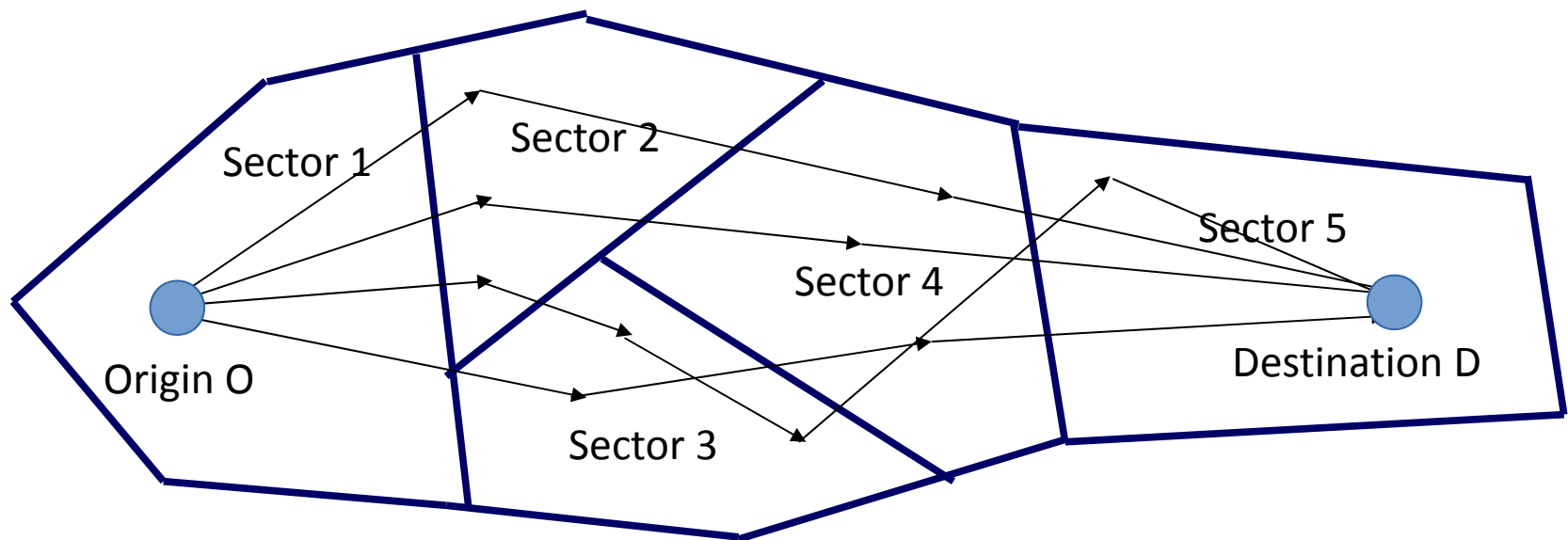
TACTICAL PHASE: managing the trajectories

Maintain the planned number of trajectories in each sector and avoid that they crash into each other;

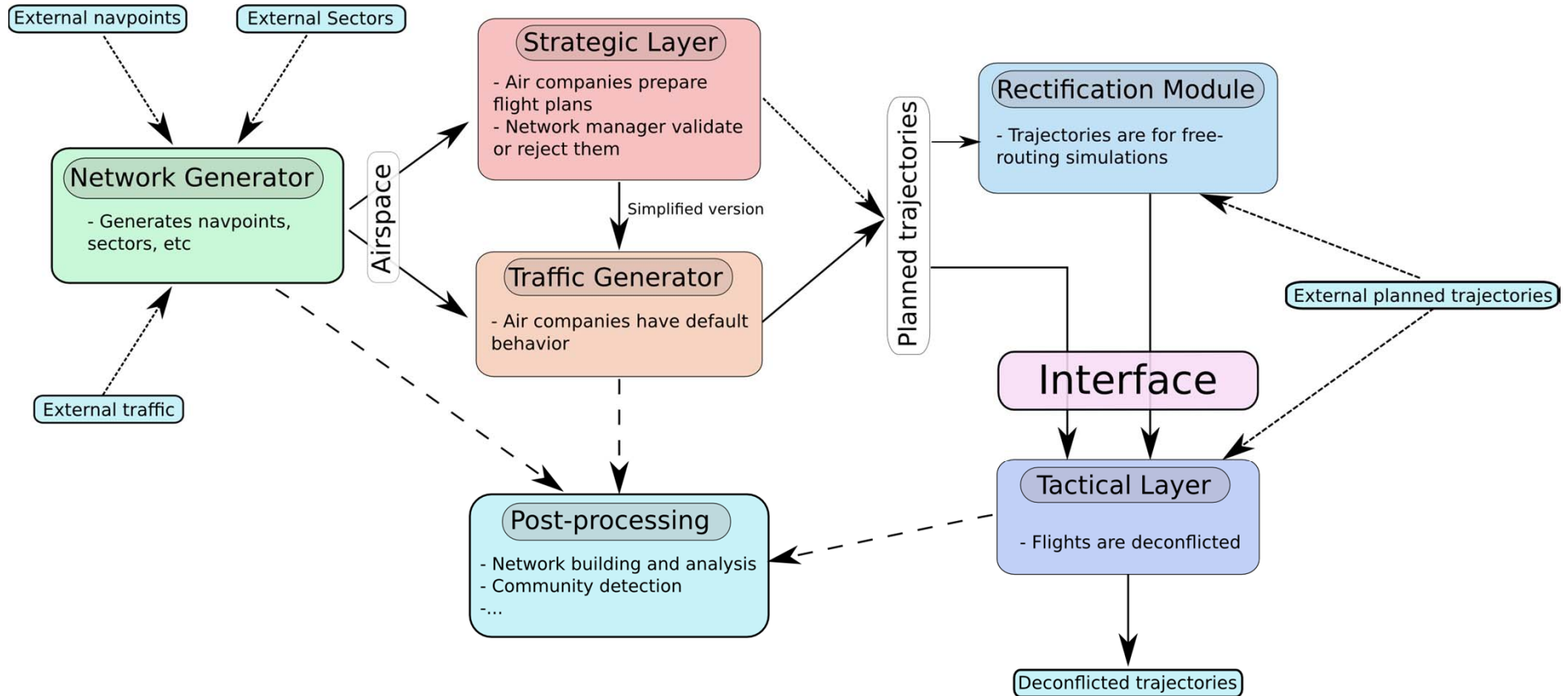
Take into account congestions due to ground delays;

Take into account changes due to extreme weather events or STRIKES;

Take into account airspace closures due to existing military areas.



ELSA Air Traffic Simulator - overview



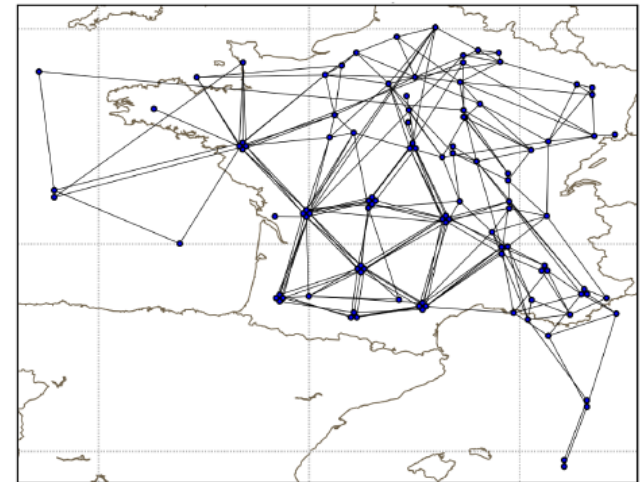
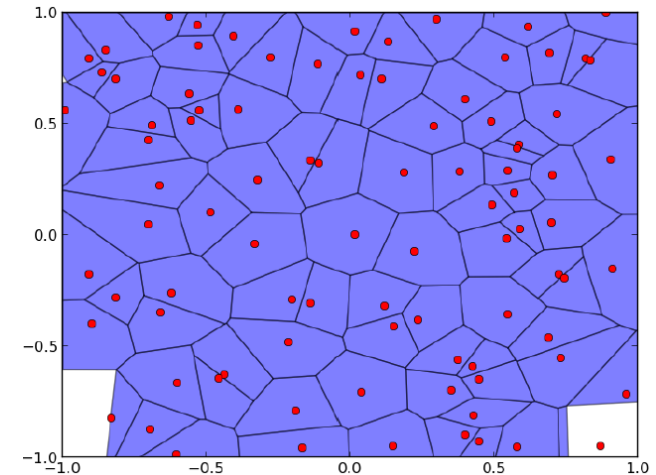
MODULARITY

STRATEGIC layer: Network Generator

The network generator module allows:

- To generate the spatial distribution of navigation points or use external data,
- To compute the navigation points network edges with a triangulation or use external data,
- To generate sectors at random, using a Voronoi tessellation for the boundaries or use external data,
- To compute time of travels between edges of navigation points or use external data.

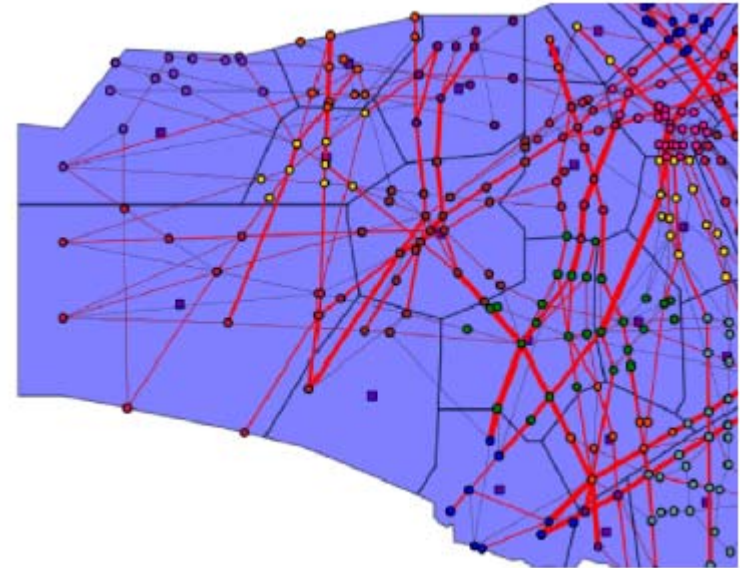
User can fully specify the network and the sectors or use the module in a semi-automated way.



Capacity constraints

STRATEGIC layer: Traffic generator

Traffic generator can be used to generate synthetic traffic on a given network of navigation points + sectors **making sure that no sector is overloaded.**



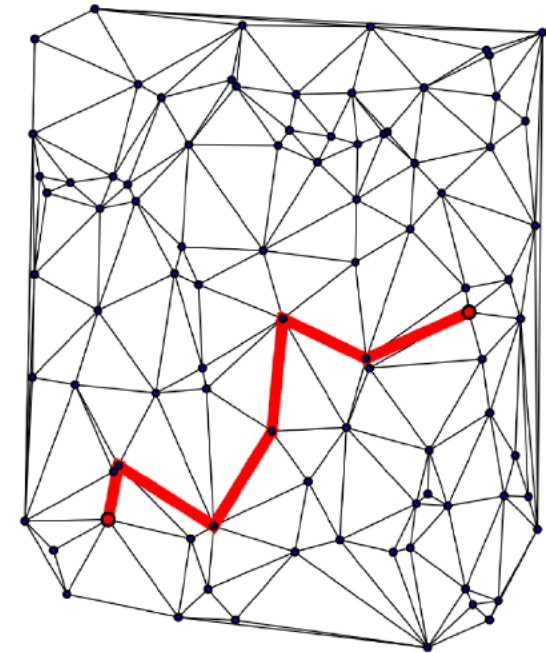
The user can specify:

- a total number of flights,
- a distribution of flights per pair of entry/exit points,
- some capacities for the sectors.

STRATEGIC layer: Traffic generator

More complex and realistic

- User can define:
 - Departure waves
 - Airlines cost-functions:
$$c(\rho, t) = \alpha|\rho| + \beta(t - t^0)$$
 - $\alpha \gg \beta$: “low-cost” companies

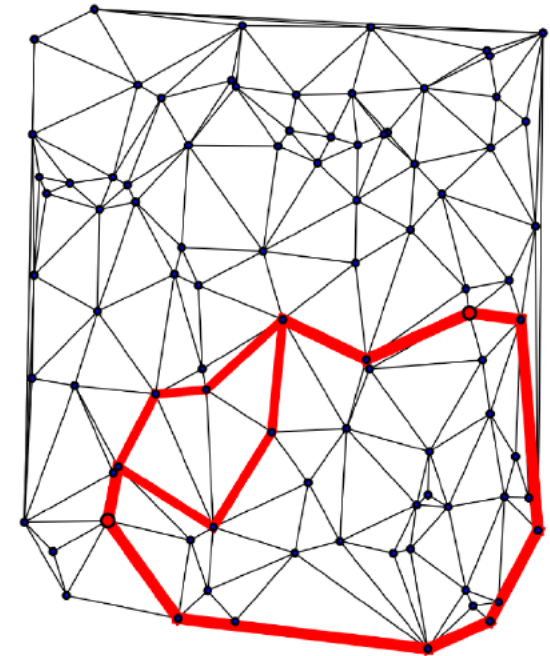


Length and delay

STRATEGIC layer: Traffic generator

More complex and realistic

- User can define:
 - Departure waves
 - Airlines cost-functions:
$$c(\rho, t) = \alpha|\rho| + \beta(t - t^0)$$
 - $\alpha \gg \beta$: “low-cost” companies
 - $\alpha \ll \beta$: “traditional” companies



HETEROGENEITY of AGENTS: different strategies

Length and delay

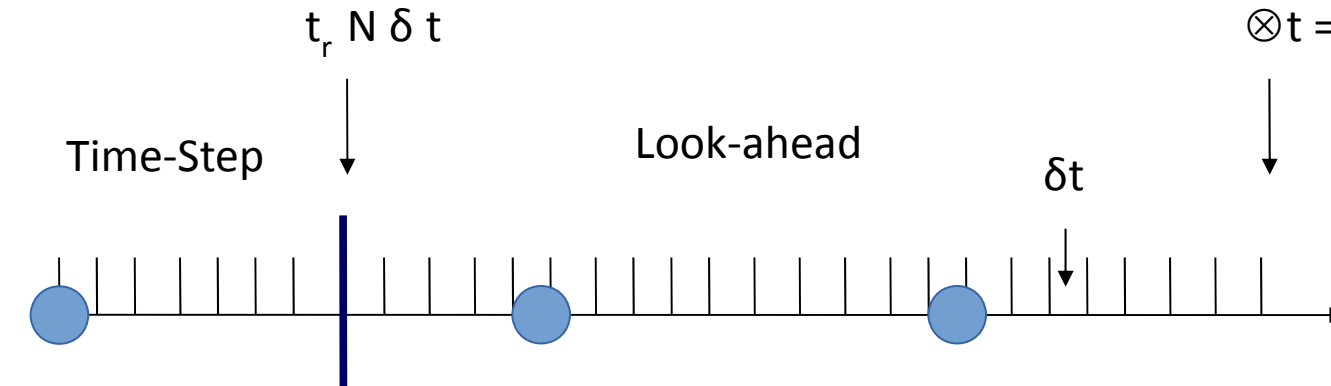
TACTICAL layer: Time-Step and Look-ahead

● *navigation points*, i.e. fixes in the trajectory

$$\otimes t = 10 \text{ min}$$

$$\delta t = 8 \text{ sec}$$

$$\otimes t = N \delta t$$



Perfect Forecast

Noised Forecast

δv is a variable uniformly distributed in $[-\sigma_v, \sigma_v]$.

$$V_{\text{ATCO}} = V$$

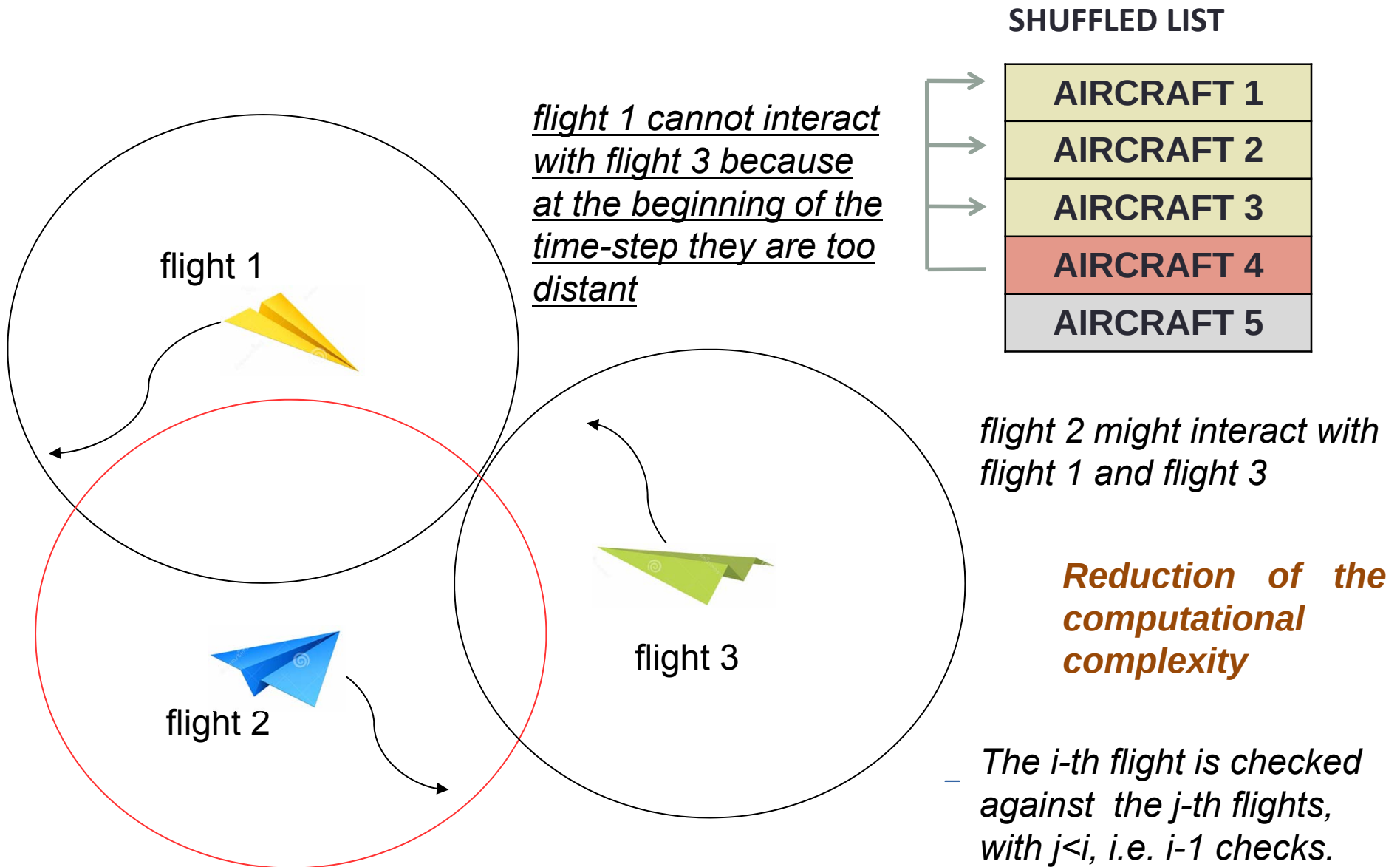
$$V_{\text{ATCO}} = V (1 + \delta v)$$

It implies a time degradation of precision by which a controller estimates the position of the aircraft

After each time-step the ABM updates the position of the flight with the position in $t_r N$, i.e. time-intervals are overlapping.

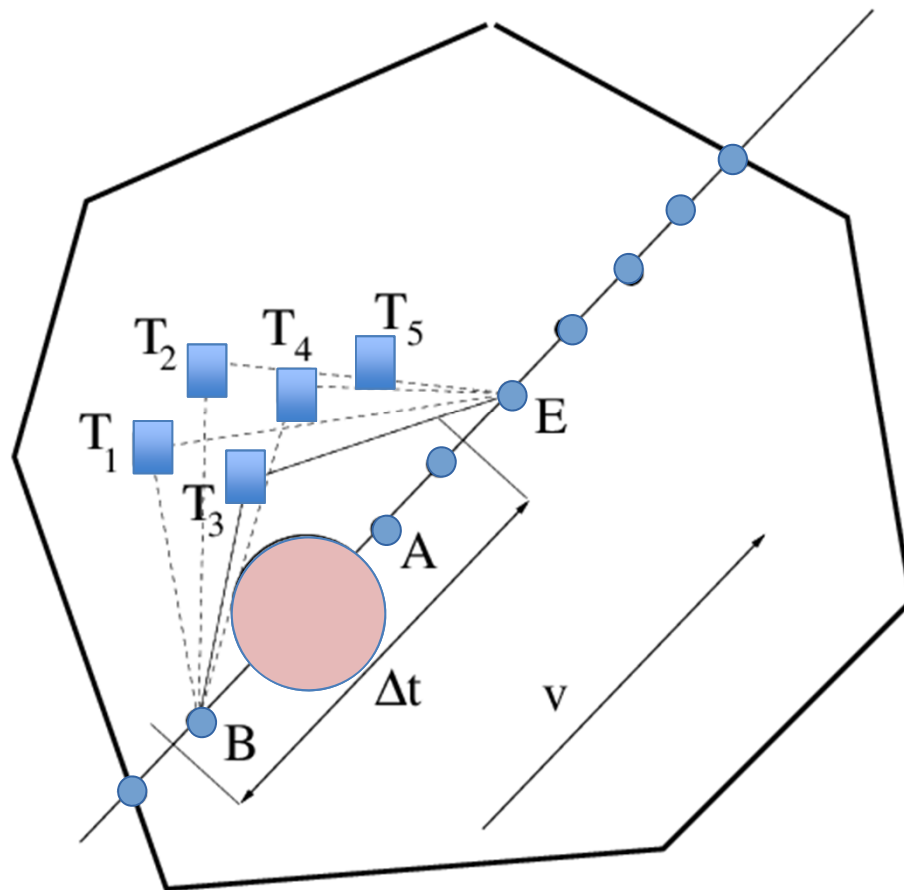
Trajectories are taken from the strategic layer as well as from real data or externally provided

TACTICAL layer: Conflict Detection



TACTICAL layer: Conflict Resolution

Re-routing



— selected
 - - - - - possible
 — planned

If a conflict is detected the algorithm selects an alternative temporary point and generates alternative paths.

If no solution is found it moves the E point forward

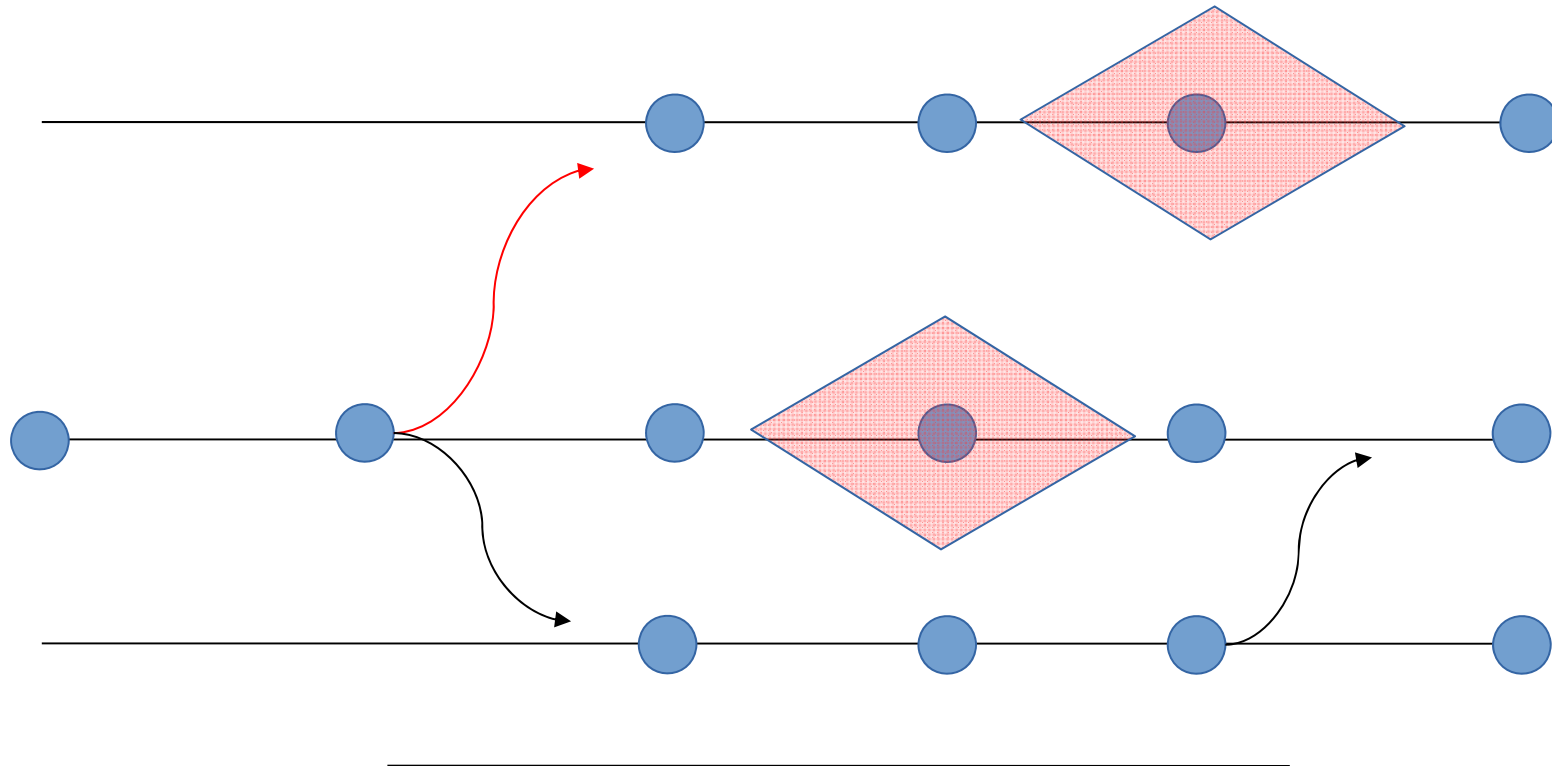
Constraints:

- $\alpha_{in} , \alpha_{out} < \alpha_M$
- *The new trajectory must have minimum length*
- *E is the first navigation point in the successive time-interval of length Δt .*

TACTICAL layer: Conflict Resolution

Change of Altitude

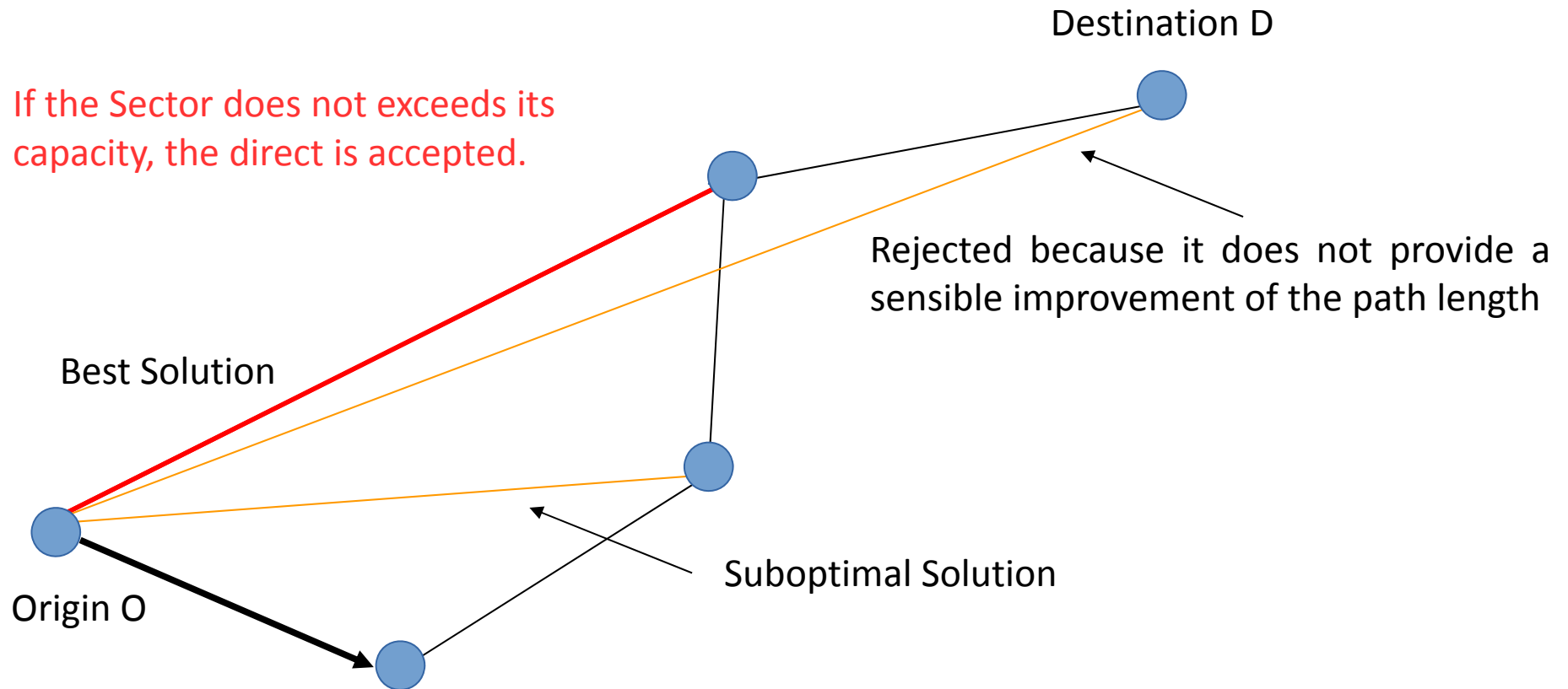
If some conflict is detected also in the new flight level then it tries -20 FL



$T_{\max}$

The Flight has to come back on the original route within a time horizon $T_{\max}$

TACTICAL layer: Directs



The Direct is accepted if it does not imply a conflict in $T_{\max}=20$ min
The flight has to come back to the original route within $T_{\max}=20$ min
Sensitivity threshold on the angle: 1 degree

TACTICAL layer: Directs

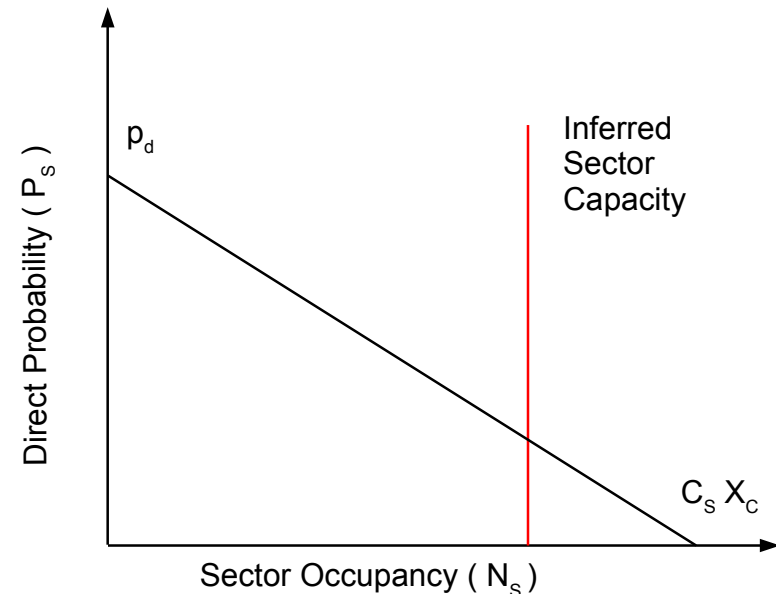
In order to simulate a multi-sector airspace, the probability to issue a direct should be dependent by the workload and the capacity of each sector. Let C_s the inferred **(from real data)** capacity of the s -th sector, and $P_s(N_s)$ the probability to issue a direct in the s -th sector. For the sake of simplicity we modelled $P_s(N_s)$ as a linear decreasing function of N_s , where N_s is the number of flight are crossing the s -sector within a 1-hour time-window.

Such linear law is described in terms of two parameters (p_d , x_c).

The first $P_s(N_s = 1) = p_d$ is the probability to issue a direct if just one flight is in the airspace.

The second x_c is obtained imposed that no direct can be issued if $N_s > x_c C_s$, i.e. $P_s(N_s > x_c C_s) = 0$.

x_c has therefore tells us of which factor the inferred capacity is indeed exceeded by each controller, therefore it tells us about the sensitivity of the ATCOs towards the traffic in that sector.



Data Input Generation

We first generate data in the current scenario

I – real data

II – artificial data calibrated on real data without capacity constraints

III – artificial data calibrated on real data with capacity constraints using the strategic layer

IV – fully artificial data using the strategic layer

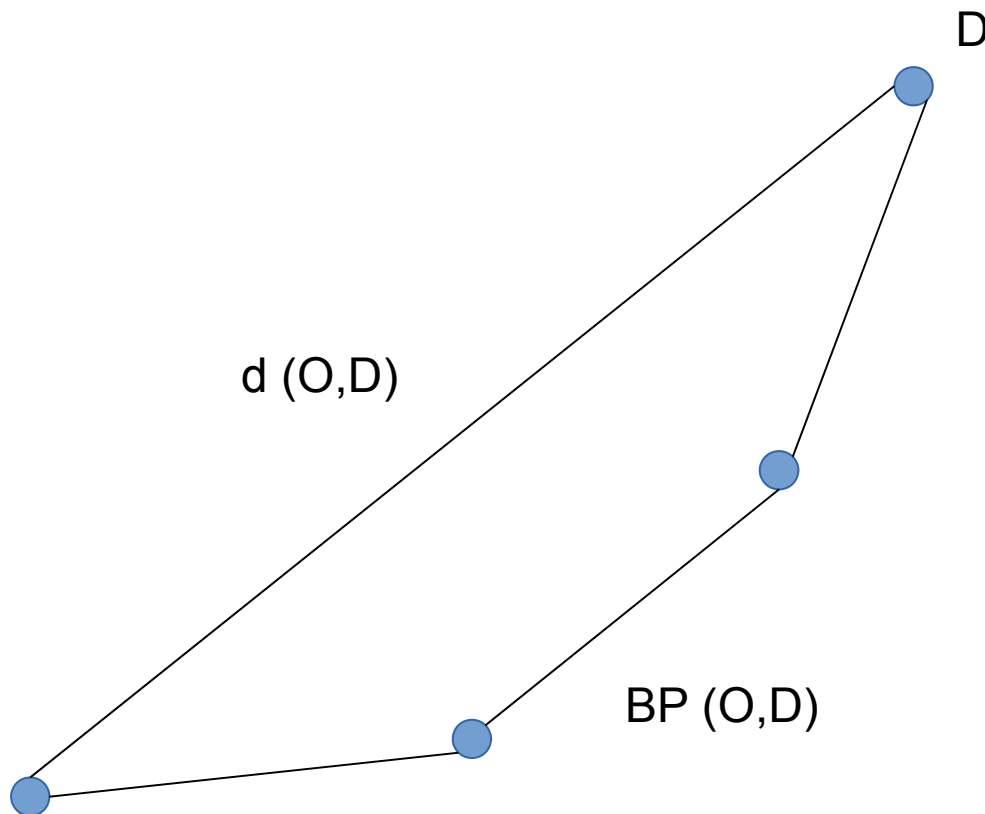
We then move to the SESAR scenario in a controlled way

We use the rectification module to create intermediate scenarios between the CURRENT and the SESAR ones.

This would allow to study the transition from CURRENT to SESAR.

Data Input Generation

ELSA Air Traffic Simulator – Rectification module



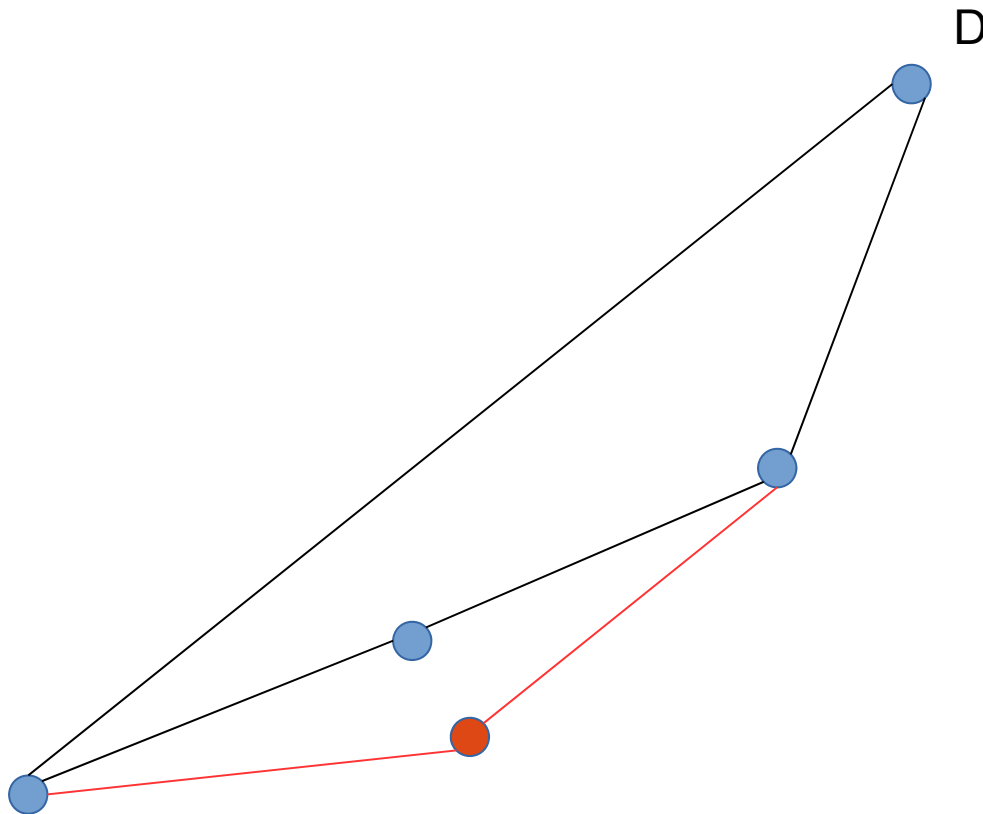
$$Eff = \frac{\sum_{i=1}^{N \text{ flights}} d(O_i, D_i)}{\sum_{i=1}^{N \text{ flights}} BP(O_i, D_i)}$$

Eff = 0.97 **CURRENT Scenario**

Eff = 1.0 **SESAR Scenario**

Data Input Generation

ELSA Air Traffic Simulator – Rectification module



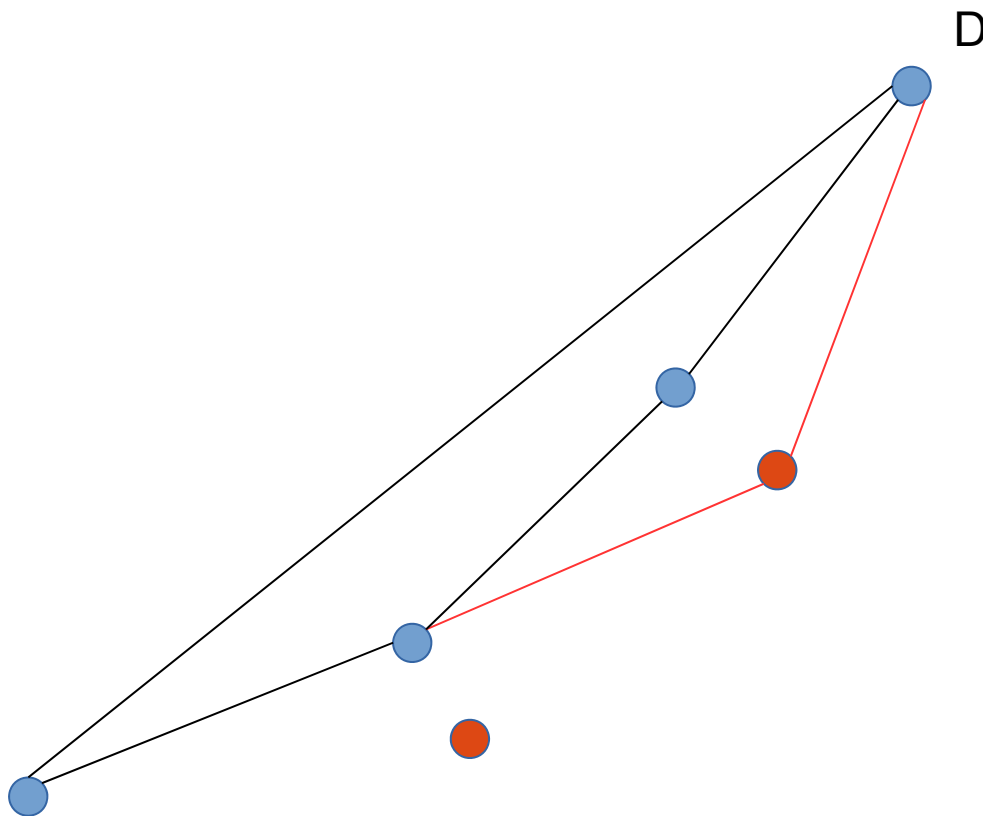
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Data Input Generation

ELSA Air Traffic Simulator – Rectification module



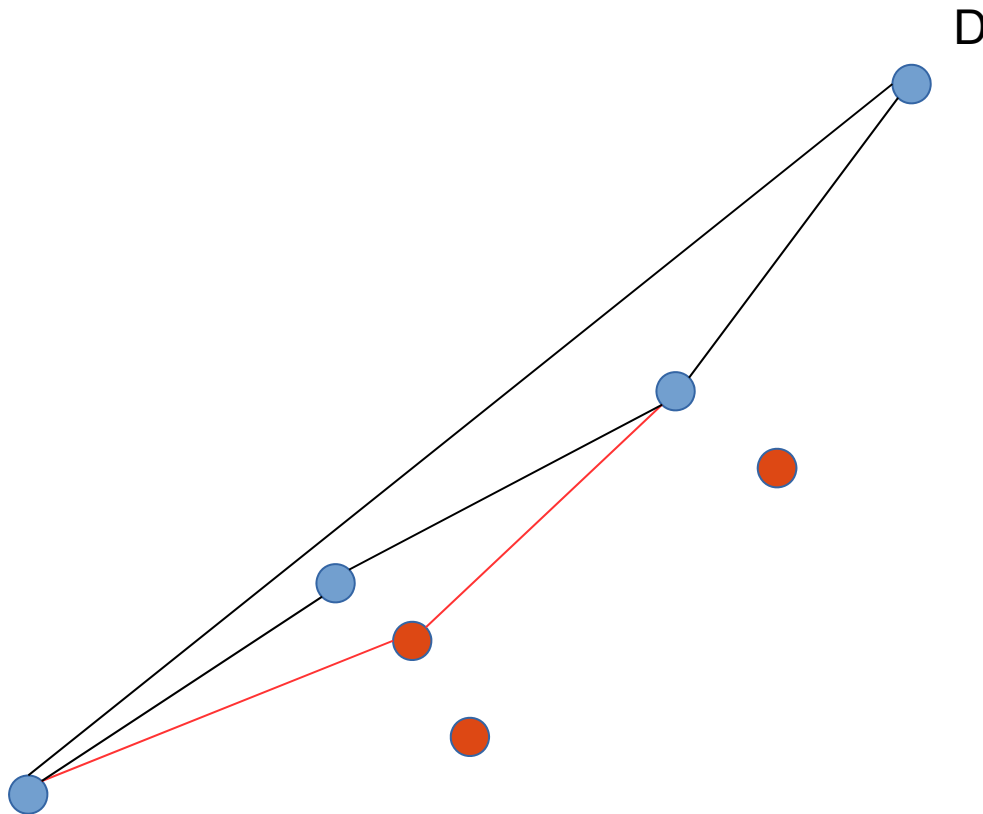
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Data Input Generation

ELSA Air Traffic Simulator – Rectification module



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Eff = 0.97 **CURRENT Scenario**

Eff = 1.0 **SESAR Scenario**

Model's parameters

ID	Parameter	Description	Type
1	Δt	Length of the time-step. This is also related to the controller's look-ahead.	FP
2	δt	Length of the elementary time-intervals.	FP
3	t_r	Fraction of Δt by which we move the overlapping time-steps.	FP
4	v	aircraft velocity	CD
5	σ_v	Range of the noise introduced in the estimation of the aircraft velocity	CV
6	D_{max}	Radius of the circle centered in B where we look for temporary navigation points potentially relevant for performing a re-routing.	FP
7	α_M	Maximum angle of deviation between planned and modified trajectory.	CV
8	T_{max}	Maximal temporal distance between the navigation point B and navigation point E that identify when a deviated portion of flight trajectory starts and ends.	FP/CV
9	p_d	Probability to try to issue a direct.	CD/CV
10	L_s	Sensitivity threshold for issuing a direct.	FP/CV
11	v_{min}, v_{max}	minimum/maximum velocity of aircraft present in the ACC	CD
12	C_S	Center of each shock.	FP/CD
13	S_m	Average number of shocks per time-step per flight-level.	FP/CD
14	D_S	Temporal duration of each shock.	FP/CD
15	R_S	Radius of each shock.	FP/CD
16	FL_{min}, FL_{max}	Minimum/maximum flight level where shocks are generated.	FP/CD

FP - free parameter, to be chosen according to the type of experiments one wants to perform.

CD - parameter that needs to be calibrated from data.

CV - parameter that needs to be calibrated according to the interviews performed with ATM experts and ATCOs.

ELSA Air Traffic Simulator – Code release

Open source: **freely downloadable and usable**

The code is released under the GPL version 3

<https://github.com/ELSA-project/ELSA-ABM>.

Github provides free hosting as well as handy tools for distributed development, like a wiki, an issue tracker, etc.

ELSA Air Traffic Simulator – Code release

Using the ELSA Air Traffic Simulator

Prerequisites:

- Basic knowledge of Python for the strategic layer,
- No knowledge of C **OR** no knowledge of Python for the tactical layer
- Some basic knowledge of UNIX commands.

Support:

- Install guide
- Basic documentation
- User guide
- Unit tests

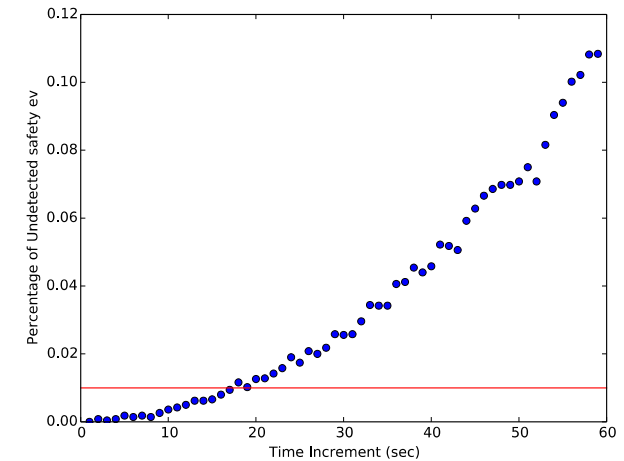
ELSA Air Traffic Simulator – Code release

Using the ELSA Air Traffic Simulator *Tutorials*

- Plugging a custom shocks module
 - Modeling weather phenomena, airspace closures
- Using a customized airspace generator
 - Generate different airspace structures (sectors shape, dimension, capacity, airways, navpoint location)
- Modification of the conflict resolution procedure
 - Customize the controlling parameters in each area of the airspace at different granularity levels (sector, FIR, FAB)

Calibration for data input generation

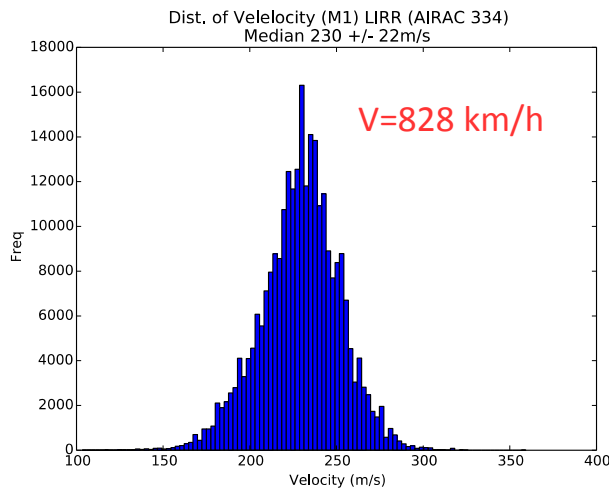
ID	Parameter	Description	Type
1	Δt	In section 4.1 and 4.2 $\Delta t = 20$ min. In section 4.3 we changed this parameter up to 60 min	FP
2	δt	8 seconds	FP
3	t_r	0.5	FP
5	σ_v	In section 4.1 and 4.2 $\sigma_v = 0$. In section 4.3 we swept this parameter	CV
6	D_{max}	100 km	FP
7	α_M	0.275 rad, i.e. $\approx 16^\circ$	CV
8	T_{max}	$2 \Delta t$	FP/CV
10	L_s	1 km	FP/CV



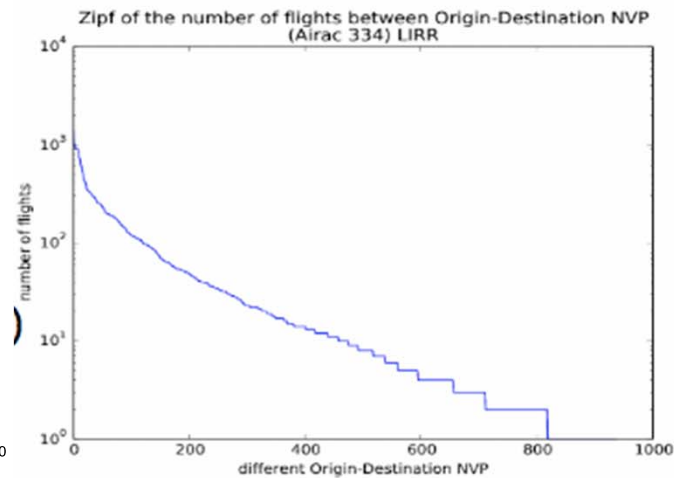
HETEROGENEITY of AGENTS: CONTROLLERS

CV parameters are *behavioral parameters* that take into account controllers' heterogeneity

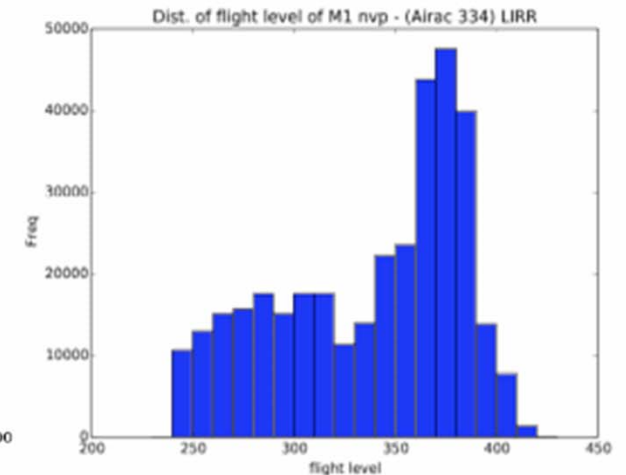
Aircraft Velocity



Origin destination pairs

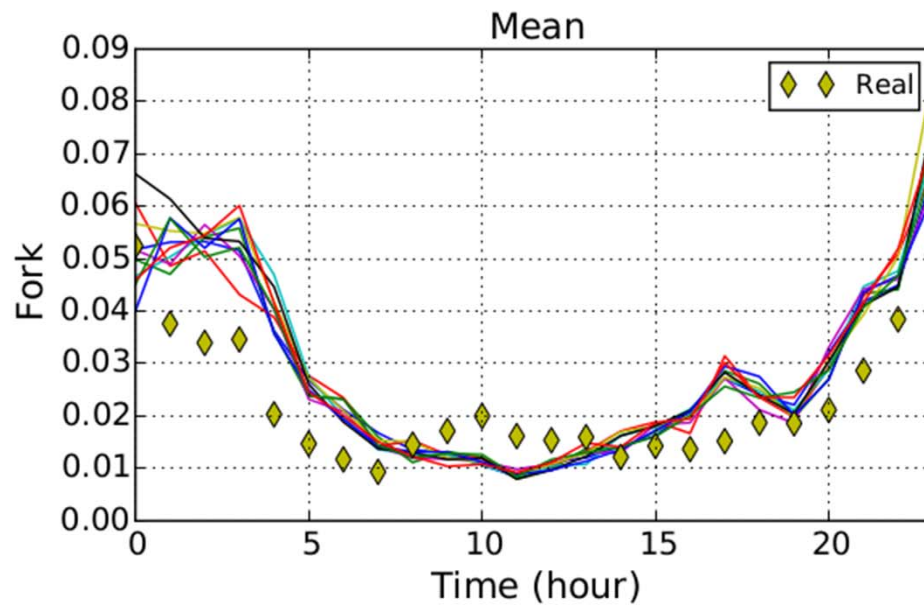
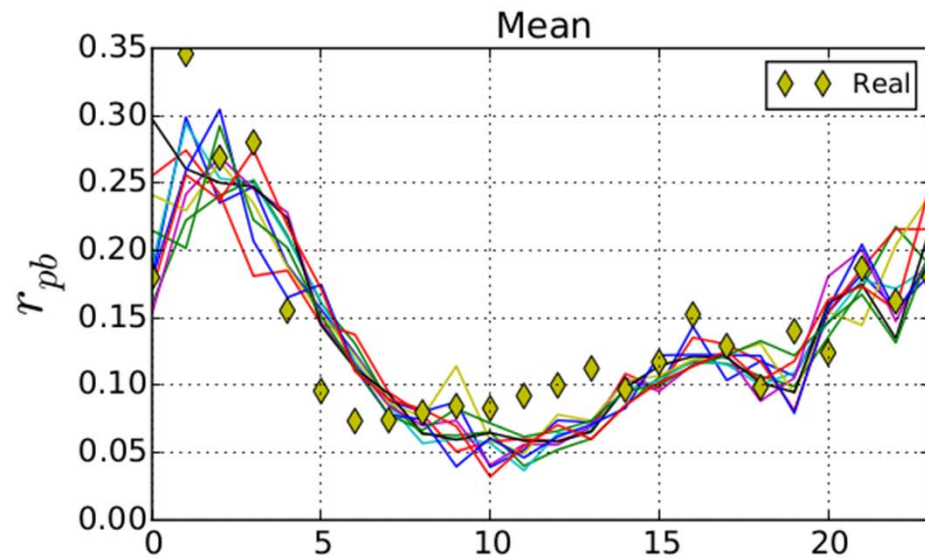


Flight levels

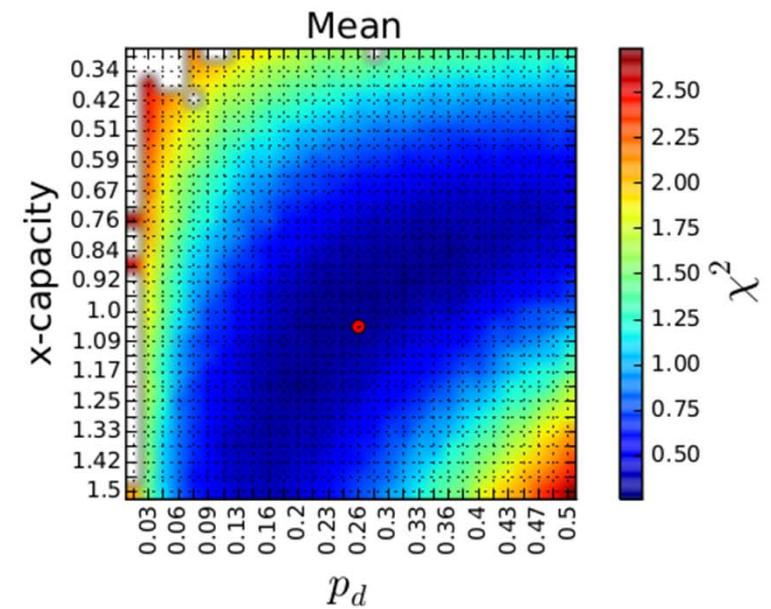


HETEROGENEITY of AGENTS: AIRCRAFT

Calibration

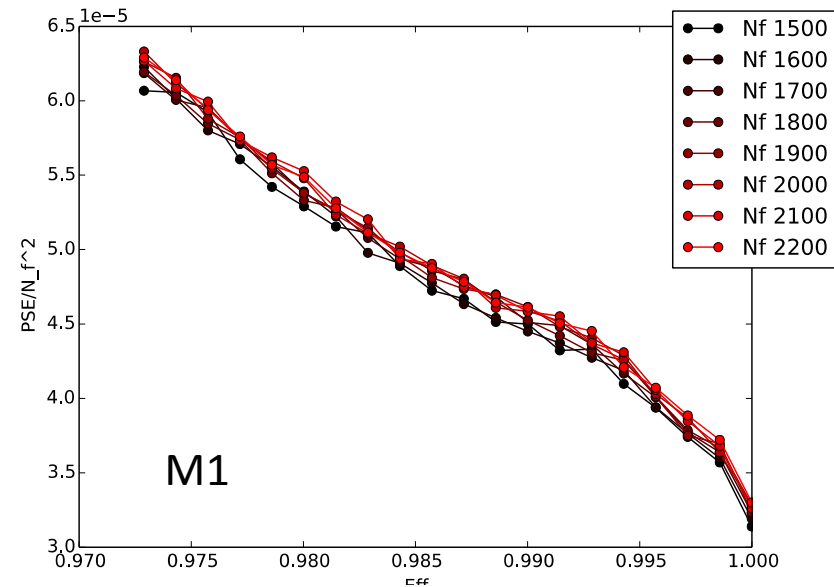
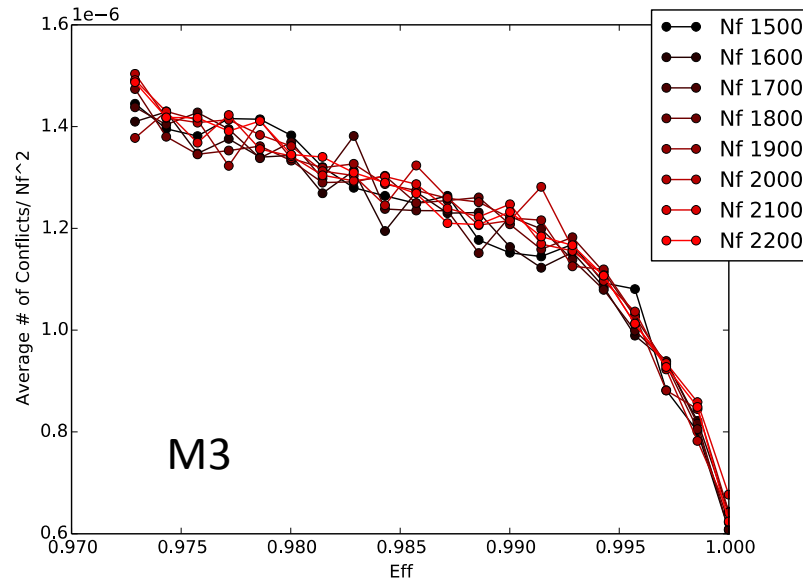


We calibrated to obtain the point-biserial correlation between angle and deviation.



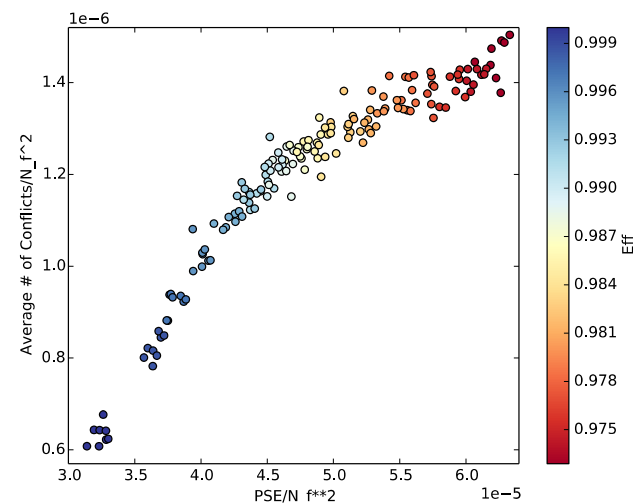
We reproduced also the intraday fork dynamic

Results – stress tests – no sectors

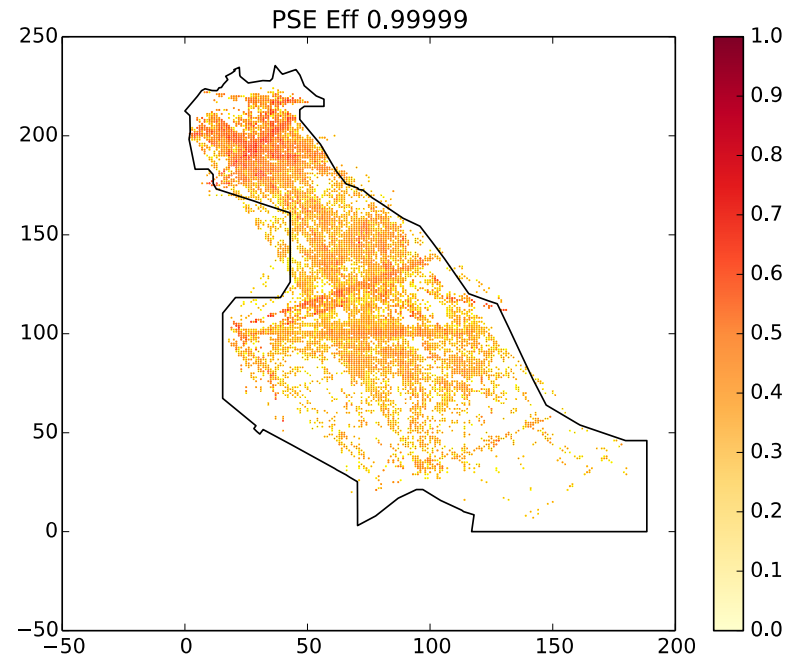
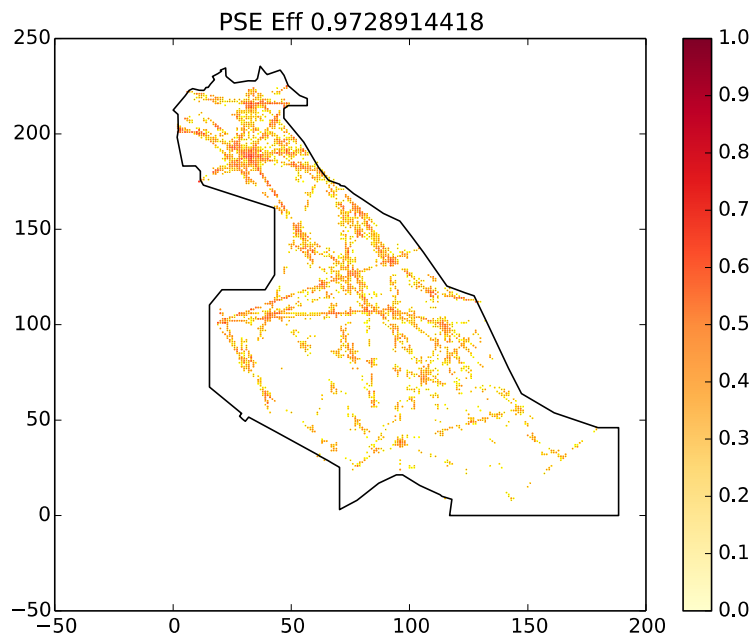


Safety events in the SESAR scenario are less than in the current scenario

However, the SESAR scenario seems to be less flexible to accommodate unexpected changes



Results – stress tests – no sectors



Furthermore, safety events are more spread all over the ACC, thus making the controllers' work less simple than nowadays.

In any case it will be **DIFFERENT**.

Results – role of the look-ahead

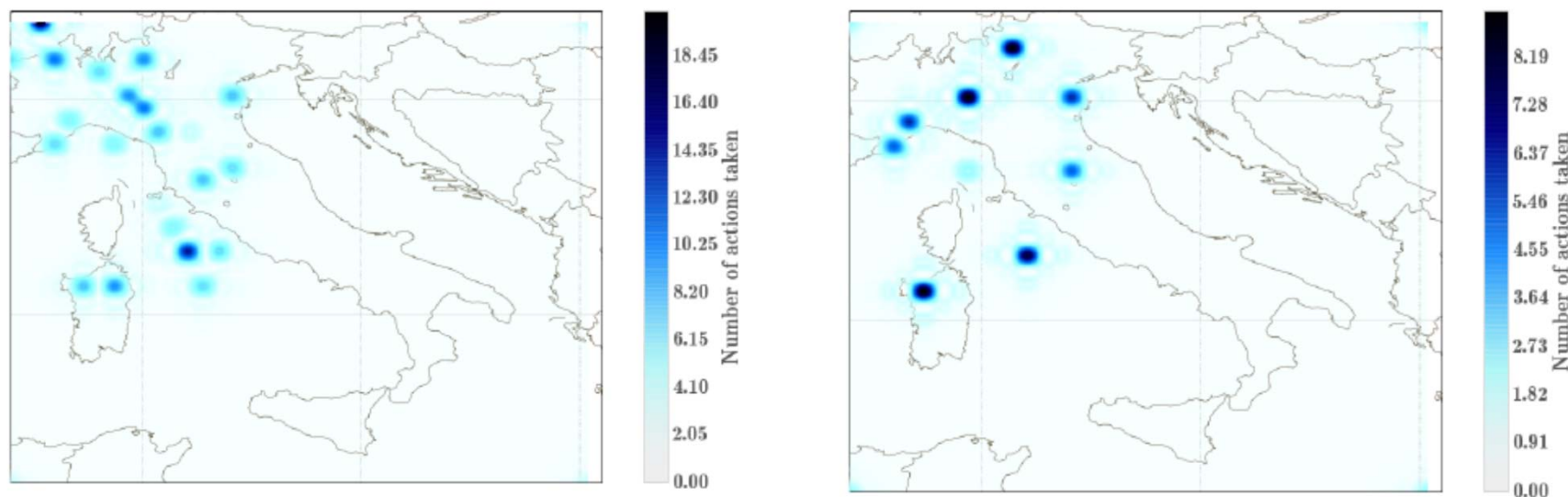
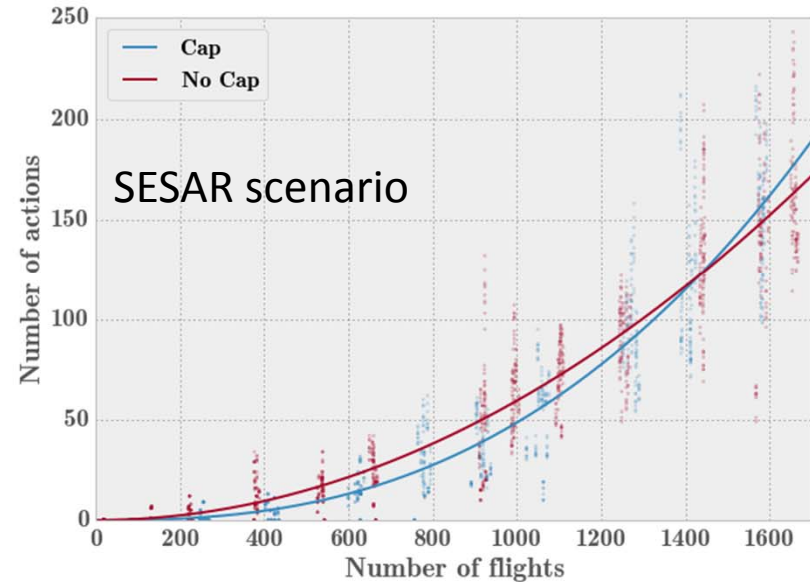
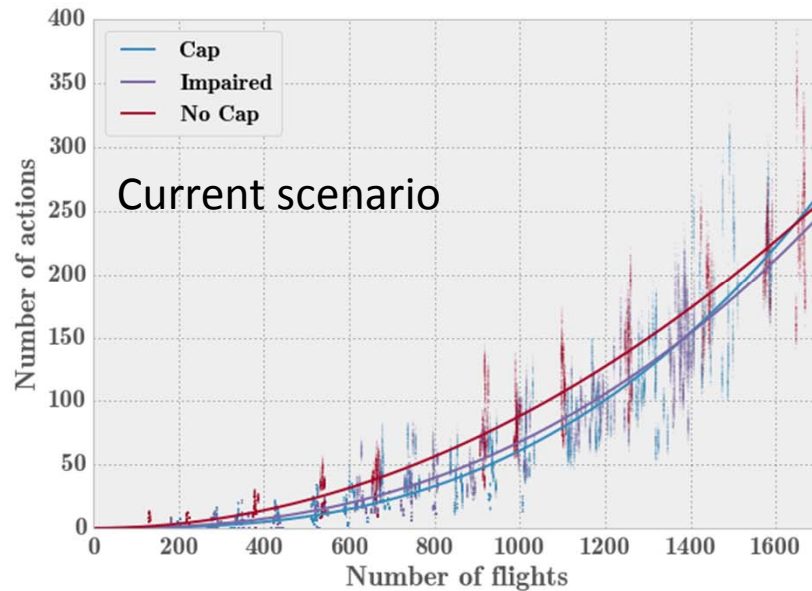


Figure 4: Spatial location of the actions taken by the controller with low (15 min, left panel) and high (40 min, right panel) look-ahead

We have preliminary results showing that the look ahead might help in making actions less spread over the whole ACC.

No shocks, sector capacities, CURRENT scenario

Results – role of capacity constraints (Multi-sector)



exponent close to 2.5

We now assume that each ACC is composed of different sectors and each sector has to fulfill capacity constraints.

In this case the N_f^2 law is no longer valid

Results – role of capacity constraints (Multi-sector)

PREFACTOR: capacity constraints induce less actions than the capacity-free case for the same number of flights.

This is due to the fact that capacities tend to spread the flights during the day. Hence the time concentration of flights decreases during peaks, which decreases the number of potential conflicts (flights are flying at different times).

EXPONENT: larger than in the free-capacity case

The same argument as above explains the super-quadratic behavior. Indeed, when the number of flights increases, it means that the capacities are less binding, since we keep the number of flights fixed as input to the strategic layer. Hence, when the number of flights increases, the number of potential conflicts increases more quickly than x^2 , because more flights are flying at similar times.

Operational benefits in SESAR scenario

- Safety improvement from the reduction of total number of conflicts and reduction of controller workload:
 - nature of controllers tasks will change (shifting from mainly conflict resolution to mainly traffic monitoring tasks.
- Improved airspace management:
 - all the actions could be taken at the entrance of the airspace. Controller will have lower workload due to more monitoring tasks and less conflict resolution and separation assurance tasks.

The End

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<http://complexworld.eu/wiki/ELSA>

<http://www.sesarju.eu/newsroom/all-news/mastering-complexity-tomorrow-atm-system>