Airspace configuration using air traffic complexity metrics

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Introduction

Complexity metrics and sector status

Opening schedule algorithm

Results

Conclusion

Questions / discussion

Introduction

"Airspace configuration" may have several meanings :

- airspace design at strategic level
- dynamic sectorization
- dynamic allocation of airspace ressources (sectors, military zones)
- ...

In our case :

- *airspace configuration* = mapping of N elementary sectors onto K controller's working positions
- *control sector* = one, or several elementary sectors merged together.

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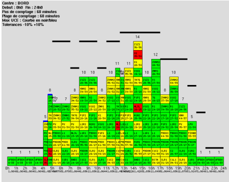

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How FMP operators build opening schedules today?

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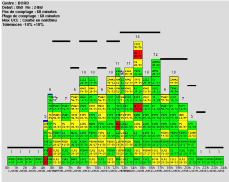

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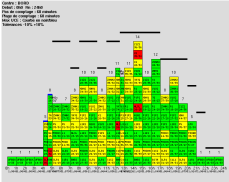

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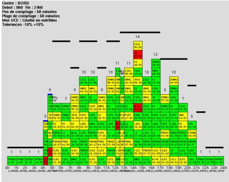

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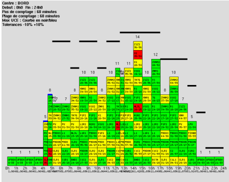

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Motivation of our research

The current process :

- small subset of all possible airspace configurations,
- relies heavily on the FMP operator's experience,
  but is NOT grounded on a solid scientific basis,

Why ?

traffic load = number of flights entering the sector between t and $t + 60$ minutes

- may be useful to smooth traffic flows (regulations in flights per period)
- is not adequate to quantify the controller's workload

$\Longrightarrow$ identify air traffic complexity factors related to controllers workload.

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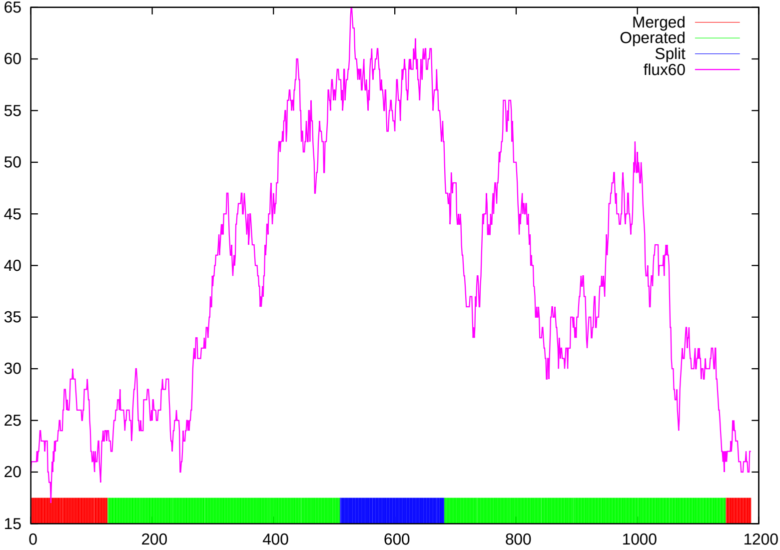
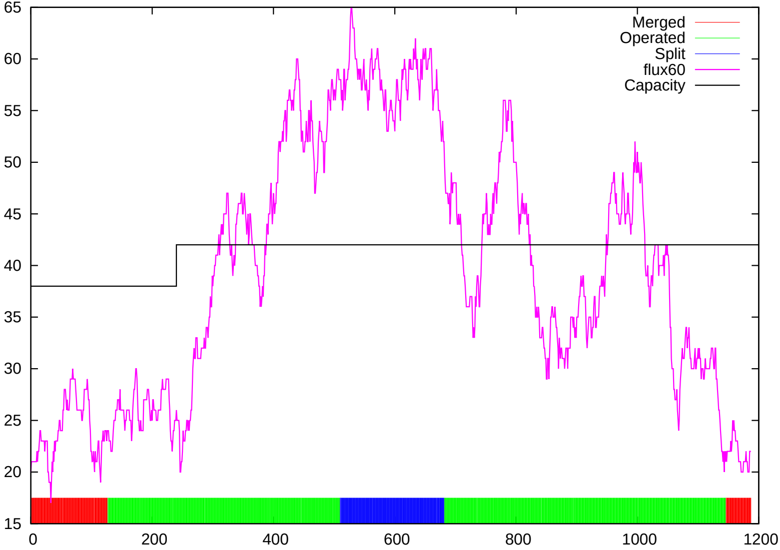
Traffic load...

N sector (Brest) : 60 mn incoming flow



Traffic load IS NOT SUFFICIENT

N sector (Brest) : 60 mn incoming flow and sector capacity



Current research

Airspace configuration

- Eurocontrol NCD team : short/medium term research, grounded on the current working method.
- NASA's NGATS Dynamic Airspace Configuration : concepts not yet defined, early stage research.

Many studies on workload / air traffic complexity :

- using different methods : linear or logistic regression, cross-sectional time-series analysis, neural networks,...
- with different *dependant variables* : physical or physiological activity, simulation models, subjective ratings,

Heavy experimental setups + active participation of controllers $\Longrightarrow$ data available in small quantities

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Our proposal

Build realistic opening schedules :

- explore all combinations of elementary sectors,
- use relevant complexity metrics to assess the controller's workload.

Use the sector status as dependent variable

- *merged* : low workload, sector is merged with other sectors,
- *manned* (or operated) : normal domain of operation,
- *split* : high workload, sector is split in several smaller sectors.

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Initial set of complexity metrics

27 metrics from various sources
(whenever a clear definition was found) :

- [Kopardekar & Magyarits (2003)]
- [Chatterji & Sridhar 2001]
- [Delahaye & Puechmorel 2000]
- Performance Review Unit
- P. Averty (CREED)
- Incoming flows (time horizon 5 to 60 minutes)

+ Sector volume V

Selection of relevant metrics

Using sector status and neural networks

Selection process : see previous publications (ICRAT, DASC).

Best model : 6 relevant metrics

- V : sector volume,
- Nb : number of aircraft,
- avg_vs : average vertical speed,
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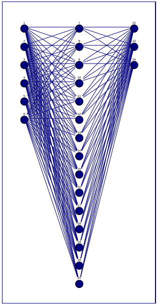
Sector status prediction

Radar tracks
Sector geometry } ⟶ complexity metrics

6 **normalized** metrics $\xrightarrow{\text{Neural network}}$ sector status probabilities



Neural network

- learns from recorded data (metrics + sector status)
- predicts sector status on fresh data inputs

Input vector $x = (x_1, ..., x_i, ..., x_p)^T$: normalized metrics
Output vector $y = (p_{merge}, p_{man}, p_{split})^T$: probabilities

$$(p_{merge}, p_{man}, p_{split})^T = \Psi(\sum_{j=1}^{15} w_{jk} \Phi(\sum_{i=1}^{6} w_{ij} x_i + w_{0j}) + w_{0k}) \quad (1)$$

$$\Phi(z) = \frac{1}{1 + e^{-z}} \qquad \Psi(z_k) = \frac{e^{z_k}}{\sum_{m=1}^{C} e^{z_m}}$$

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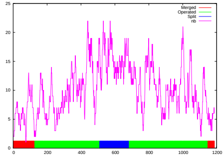
We can compute the sector status...

$$\left.\begin{array}{l}\text{Radar tracks}\\ \text{Sector geometry}\end{array}\right\} \longrightarrow \text{Complexity metrics}$$

$$\downarrow$$

$$\text{Sector status } (p_{merge}, p_{man}, p_{split})$$

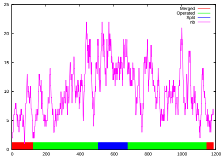


How about full airspace configurations ?

Radar tracks
Sector geometry } ⟶ Complexity metrics

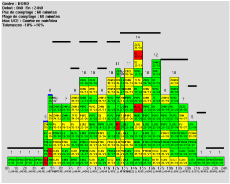
↓

Sector status $(p_{merge}, p_{man}, p_{split})$



↓

Sectors opening schedule



Opening schedule algorithm

Initial configuration (t=0) :

1 control sector ⟵ all elementary sectors

At each time step (1 minute) :

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At each time step (1 minute) :

- Decide if airspace must be reconfigured
  ⟶ check status of each control sector
- Reconfigure sectors that need to be split or merged :
  - build the set of elementary sectors
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Decision criteria

$$(p_{merge}, p_{man}, p_{split}) \xrightarrow[\text{decreasing order}]{\text{sort by}} (p_1, p_2, p_3)$$

Decision criterion D_1 :

- **merge** if p_1 is the probability p_{merge},
- **split** if p_1 is the probability p_{split}.

Decision criterion D_2 :

- **merge** if p_1 is the probability p_{merge} and $1 - p_1 < \alpha$ and $p_1 - p_2 > \eta$,
- **split** if p_1 is the probability p_{split} and $1 - p_1 < \beta$.

where α, β and η are chosen parameters.

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Subset of elementary sectors

Decision criterion

$\longrightarrow$ control sectors to split or merge

$\longrightarrow$ subset elementary sectors to recombine

With criterion D_1

we will search a better partition of the resulting subset.

Criterion D_2 triggers less reconfigurations than D_1

$\Rightarrow$ smaller subset

When D_2 triggers an airspace reconfiguration, we recombine the same elementary sectors as with D_1.

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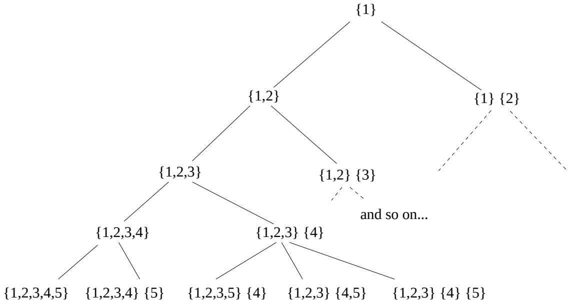
Explore all sector combinations

Searching the partitions of a set of 5 elements

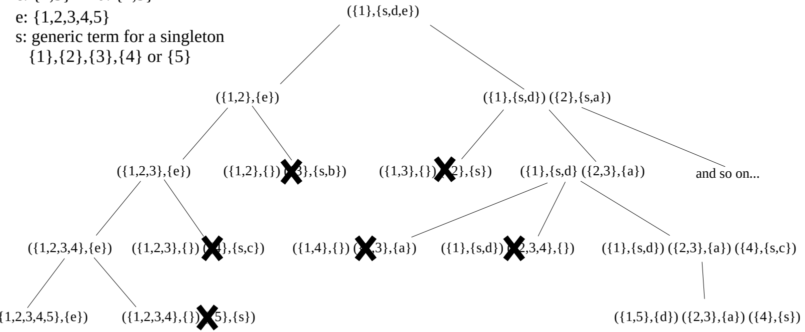


Explore all sector combinations

Searching all valid airspace configurations

Valid groups of sectors :

a: {2,3} b: {3,4}
c: {4,5} d: {1,5}
e: {1,2,3,4,5}
s: generic term for a singleton
{1},{2},{3},{4} or {5}



Select partition with minimum cost

"Ideal" configuration :

$(p_{merge}, p_{man}, p_{split}) = (0, 1, 0)$ for ALL control sectors.

Evaluate each candidate configuration :

- penalize overloads more than underloads
- penalize underloads more than configurations with only normally loaded sectors
- choose the one with the less control sectors, among otherwise equivalent configurations.

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$$eval_{config}(x,t) = \underbrace{xxxxx}_{k_1}\underbrace{xx}_{k_2}\underbrace{xxxxx}_{k_3}\underbrace{xxx}_{k_4}$$

- k_1 digits for the cost of overloads,
- k_2 digits for the number of control sectors
- k_3 digits for the cost of underloads,
- k_4 digits for the cost of normally loaded sectors.

Results

Brest ATCC, criterion D_2 with $\alpha = 0.5$, $\eta = 0.2$, and $\beta = 0.5$.

```
...
t= 258 [AOUS FZX RNG RQJ]
t= 261 [AOUS RFX RNG RQJ Z]
t= 265 [AOUS FZX RNG RQJ]
t= 266 [AOUS RFX RNG RQJ Z]
t= 281 [AOUS J Q RFX RNG Z]
t= 283 [AOUS FBRT J Q RNG RZX]
t= 304 [AOUS FBRT J Q RNG X Z]
t= 317 [AOUS J Q RFX RNG Z]
t= 324 [A FBRT J O Q RNG RZX]
t= 328 [A FBRT J O Q RNG X Z]
t= 332 [AOUS FBRT J Q RNG X Z]
t= 335 [AOUS FBRT G J N Q X Z]
t= 337 [AOUS J Q RFX RNG Z]
t= 338 [AOUS FBRT G J N QS QU X Z]
t= 342 [AOUS FBRT J QS QU RNG X Z]
t= 343 [AOUS J QS QU RFX RNG Z]
...
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...
```

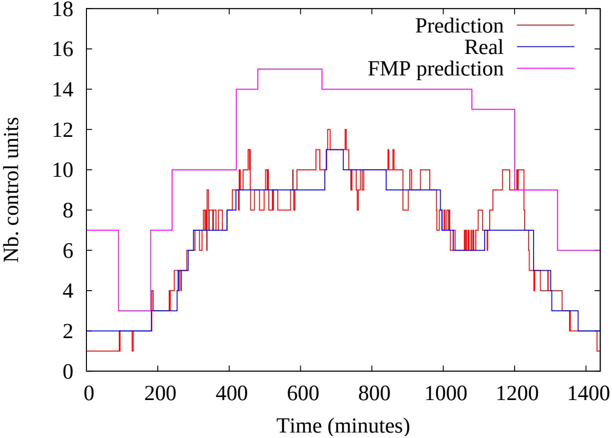
Results

Real airspace configurations for Brest ATCC (2003, June 1st)

```
...
t= 254 [NGA ROQ RFJ RZX]
t= 257 [NGA ROQ J FBRT RZX]
t= 285 [N RGA ROQ J FBRT RZX]
t= 300 [N RGA ROQ J FBRT ZXU ZXSI]
t= 394 [N RGA ROQ J FBRT ZXU ZXI ZXS]
t= 419 [N A G ROQ J FBRT ZXU ZXI ZXS]
...
```

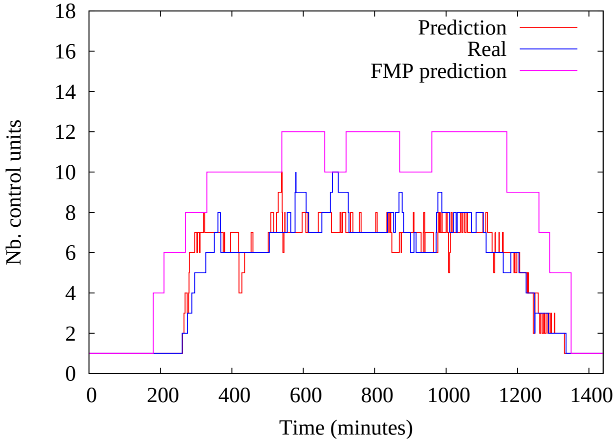
Results

Number of control sectors
Brest ATCC (2003, June 1st), with decision criterion $D2$ ($\alpha = 0.5$, $\eta = 0.2$, and $\beta = 0.5$).



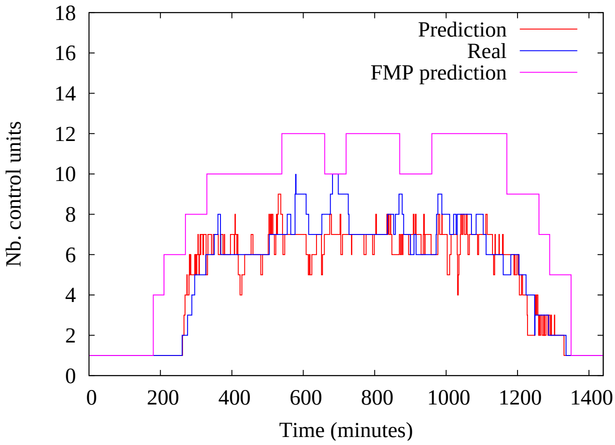
Influence of the decision criterion

Number of control sectors
Reims ATCC (2003, June 2nd), with decision criterion $D1$.



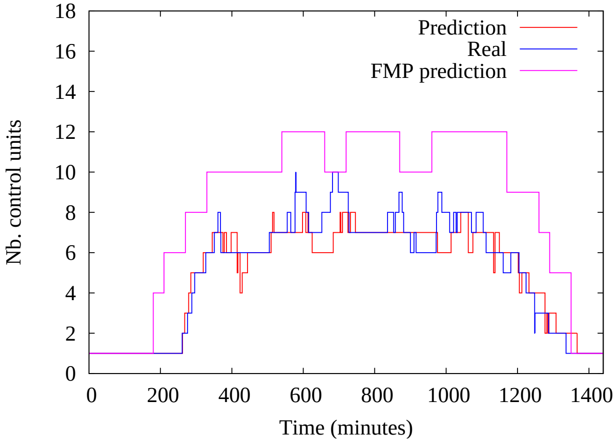
Influence of the decision criterion

Number of control sectors
Reims ATCC (2003, June 2nd), with decision criterion $D2$ ($\alpha = 0.5$, $\eta = 0.2$, and $\beta = 0.5$)



Results

Reims ATCC (2003, June 2nd), with decision criterion $D2$ ($\alpha = 0.1$, $\eta = 0.2$, and $\beta = 0.3$)



Influence of the decision criterion

Choice of α, η, and β for D_2

- Best compromise so far : $\alpha = 0.10$, $\eta = 0.2$, and $\beta = 0.3$.
- More reactive when workload increases than when it drops down.

This seems to reflect the actual controllers behaviour.

Needs to be confirmed by a parametric study : quantify correlation between computed and real configurations.

Still many configuration changes
$\longrightarrow$ status prediction quality, when using raw metrics.

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The proposed algorithms show good results :

- realistic airspace configurations,
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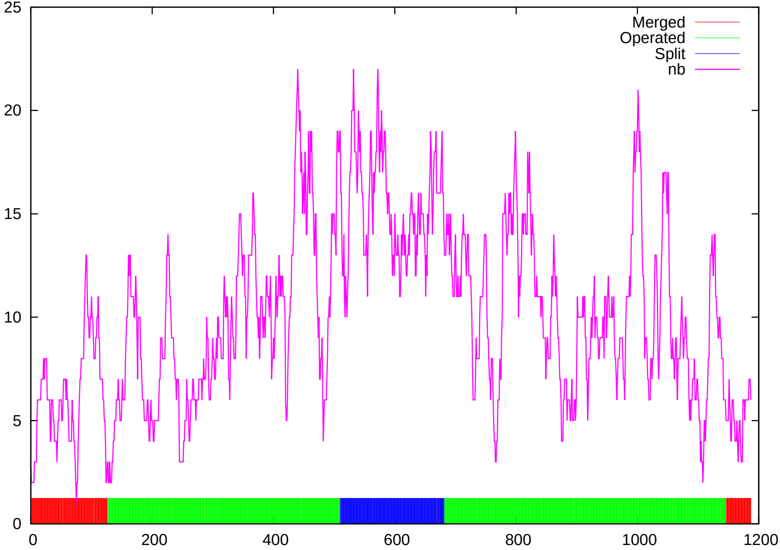
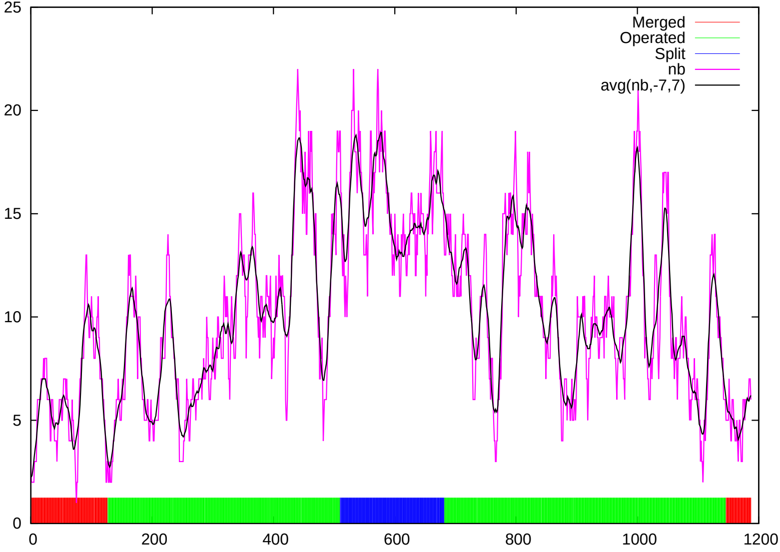
Raw metrics show high variations



Use smoothed metrics ?



Future work

Improve sector status prediction

$\longrightarrow$ try smoothed/aggregated metrics

Improve opening schedule's algorithm :

Currently : only local recombinations

- not a problem when splitting sectors,
- but merging a sector requires neighbours that also need to be reconfigured.

$\Rightarrow$ cannot merge sectors which are not neighbours,

Solution : trigger a full reconfiguration (B&B) when several connex components.

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Perspectives

Sector status prediction

only representative of how control sectors are operated today.

- macroscopic workload indicator for control room manager ?
- what-if function for tactical re-routing ?
  may not be accurate enough.
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Realistic opening schedule

If it can be predicted with enough anticipation (several hours ? 1 or 2 days ?) :

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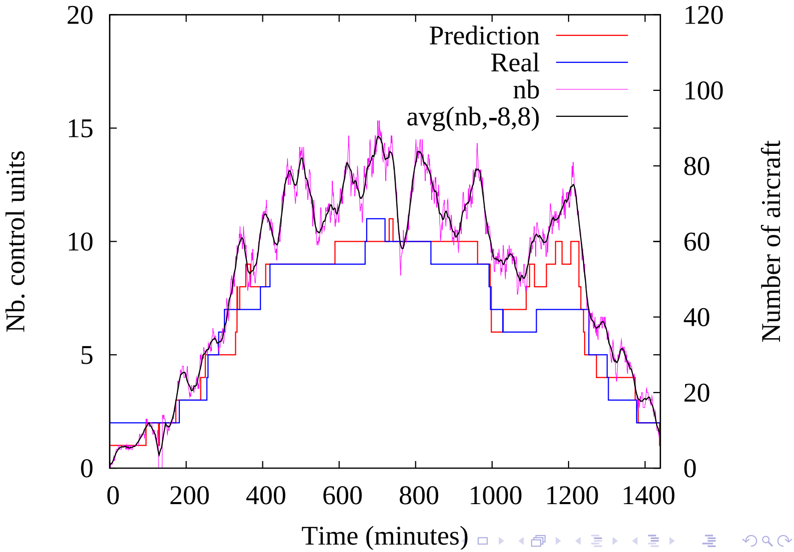
End of presentation...

... any questions ?

Opening schedule with smoothed metrics (Brest ATCC, 2003, June 1st)



Neural network's training

Classification problem –> assign each input vector x to a class *merged*, *armed*, or *split*

Training

- Choose the weights and biases so as to minimize the cross-entropy :

$$E(w) = -\sum_{n=1}^{N} \sum_{k=1}^{C} t_k^{(n)} ln(y_k^{(n)})$$

- considering N data samples (*train* set), and $C = 3$ classes,
- where t is the target vector (known class vector)
  - *merged* class : $t = (1, 0, 0)^T$
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Cost functions

- $N_{units}(t)$ the number of airspace units (control sectors) in the configuration at time t,
- $C_+(t) = \sum_{x \in config} \delta_{split}(x,t).p_{split}(x,t).N_{sect}(x)$,
- $C(t) = \sum_{x \in config} \delta_{man}(x,t).(1 - p_{man}(x,t))$,
- $C_-(t) = \sum_{x \in config} \delta_{merge}(x,t).p_{merge}(x,t).N_{sect}(x)$.

where $\delta_{split}(x,t) = 1$ if $p_{split}(x,t)$ is greater than $p_{man}(x,t)$ and $p_{merge}(x,t)$, and is equal to 0 otherwise.

Evaluate an airspace configuration

$$eval_{config}(x,t) = \underbrace{xxxxx}_{k_1}\underbrace{xx}_{k_2}\underbrace{xxxxx}_{k_3}\underbrace{xxx}_{k_4}$$

$$\begin{aligned} eval_{config} = \; & 10^{k_2+k_3+k_4} \times N(k_1, C_+(t)) \\ & +10^{k_3+k_4} \times N(k_2, N_{units}(t)) \\ & +10^{k_4} \times N(k_3, C_-(t)) \\ & +N(k_4, C(t)) \end{aligned}$$

where $N(k,c) = \lfloor max(0,(10^k - 1) - c) \rfloor$