The use of gas sensors systems for environmental odour monitoring: potential, limitations, and future perspectives

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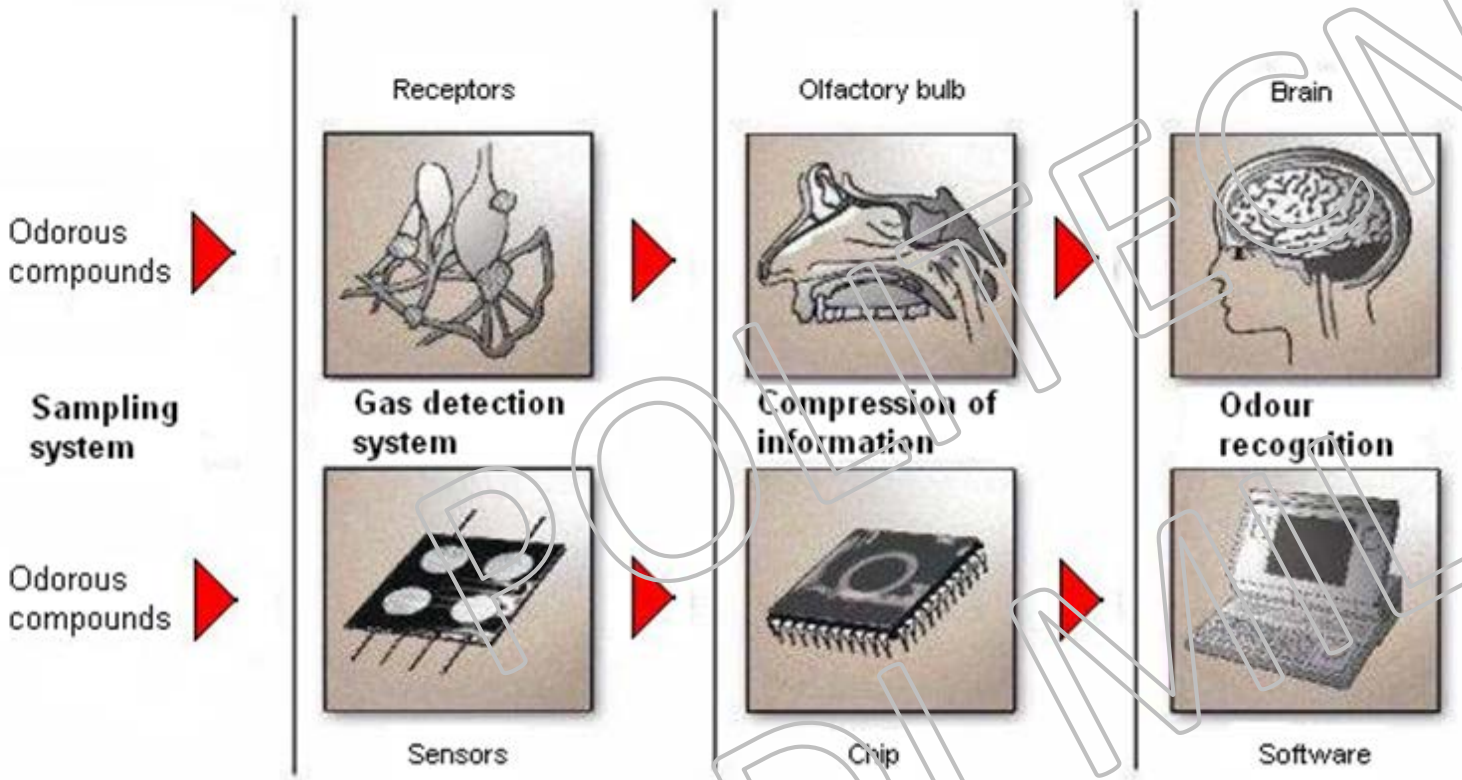
ODOUR IMPACT ASSESSMENT METHODS

	MEASUREMENTS		MATHEMATICAL METHODS
	SENSORIAL (HUMAN NOSE)	INSTRUMENTAL	
EMISSIONS/ SOURCES 	• Dynamic olfactometry (EN 13725:2003) • Gas-chromatography-olfactometry (GC-O)	• Chemical analysis • With speciation (GC-MS) • Single gases • Non specific • Electronic nose (IOMS)	• Odour Emission Factors (OEF) • Emission databases
IMMISSIONS/ RECEPTOR 	• Field Inspection (EN 16841:2016) • Field olfactometry • Citizen Science	• Chemical analysis • With speciation (GC-MS) • Single gases • Electronic nose (IOMS)	• Dispersion models

INSTRUMENTAL ODOUR MONITORING SYSTEMS (IOMS)



- With their capability to **mimic the functioning of the mammalian olfactory system**, electronic noses present the **unique advantage**, compared to other techniques, to enable the **continuous monitoring of odour emissions**

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: WHY??

- The electronic nose currently represents **the only instrument specific for odour analysis**
- It enables the **continuous analysis of ambient air** for medium-long periods aimed at:
  - **Odour detection** by signalling presence/absence of odours
  - **Odour classification**, recognition of odour provenance
  - **Odour quantification,** measurement related to odour concentration

The electronic nose is the only method capable to provide information about ODOUR QUALITY/ CLASS (no other standardized reference method!)

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: REGULATORY BACKGROUND

FRANCE:

- For **rendering plants**, if an e-Nose is used for the continuous monitoring of emissions, the frequency of mandatory olfactometric surveys is reduced (from 3 months to 1 year for emissions >100'000 ou_E/m^3 and from 6 months to 2 years for emissions < 100'000 ou_E/m^3)
  (Arrêté du 12 février 2003)

ITALY:

- Several **regional guidelines** mention the possibility to use of IOMS to integrate/ complement the dispersion modelling approach, especially where the recognition of odour provenance is needed
- Installation of e-Noses at plant fenceline for the continuous monitoring of odour concentrations is more and more frequently **prescribed in plant permits**

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: REGULATORY BACKGROUND

The European Industrial Emission Directive (IED, 2010)

DIRECTIVES

DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 24 November 2010

on industrial emissions (integrated pollution prevention and control)

(Recast)

(Text with EEA relevance)

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32010L0075&qid=1643234096360

IED: SUBJECT AND SCOPE

- This Directive lays down rules on **integrated prevention and control of pollution arising from industrial activities**.
- The Directive applies to the industrial activities giving rise to pollution referred to in Chapters II to VI:
  - Chapter II: Activities listed in Annex I
  - Chapter III: Combustion plants
  - Chapter IV: Waste incineration and waste co-incineration plants
  - Chapter V: Installations and activities using organic solvents
  - Chapter VI: Installations producing Titanium Oxide
- The Directive shall not apply to research activities, development activities or the testing of new products and processes.

In order to ensure the prevention and control of pollution, **each installation can operate only if it holds a permit** (Art. 4).

IED: ANNEX I

1. Energy industries

- Combustion of fuels in installations with a total rated thermal input of 50 MW or more
- Refining of mineral oil and gas

2. Production and processing of metals

- Production of pig iron or steel (primary or secondary fusion) including continuous casting, with a capacity exceeding 2,5 t/h
- Ferrous metal foundries with a production capacity exceeding 20 t/d
- Processing of non-ferrous metals: Surface treatment of metals or plastic materials using an electrolytic or chemical process where the volume of the treatment vats exceeds 30 m^3

3. Mineral industry

- Production of cement, lime and magnesium oxide; Production of asbestos or the manufacture of asbestos-based products
- Manufacture of glass including glass fibre with a melting capacity exceeding 20 t/d
- Manufacture of ceramic products by firing, with a production capacity exceeding 75 t/d

4. Chemical industry

- Production of organic an inorganic chemicals
- Production of phosphorous-, nitrogen- or potassium-based fertilisers (simple or compound fertilisers)
- Production of plant protection products or of biocides
- Production of pharmaceutical products including intermediates
- Production of explosives

IED: ANNEX I

5. Waste management

- Disposal or recovery of hazardous waste with a capacity exceeding 10 t/d
- Disposal or recovery of waste in waste incineration plants or in waste co-incineration plants:
  a) for non-hazardous waste with a capacity exceeding 3 t/h;
  b) for hazardous waste with a capacity exceeding 10 t/d.
- Disposal of non-hazardous waste with a capacity exceeding 50 t/d, excluding activities covered by Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment
- Landfills, as defined in Article 2(g) of Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste(1) receiving more than 10 t of waste per day or with a total capacity exceeding 25 000 t, excluding landfills of inert waste

6. Other activities

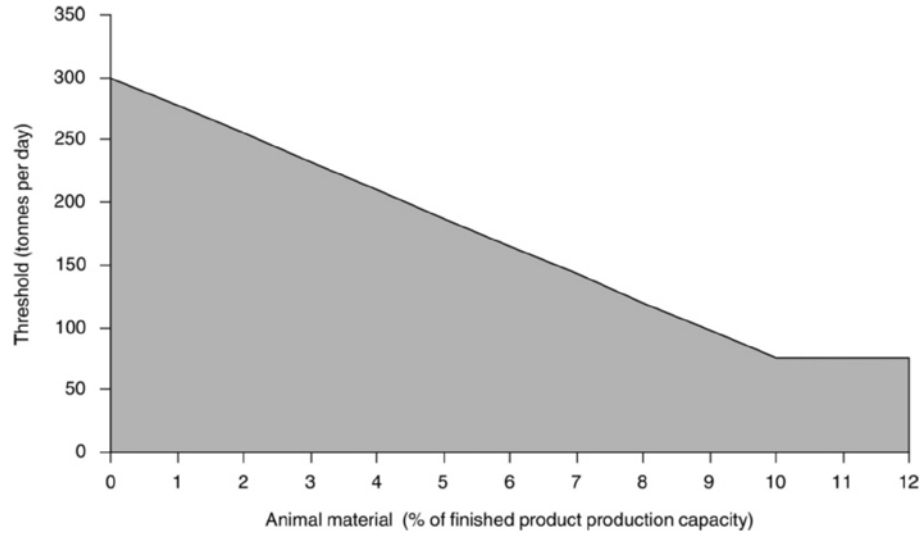
- Production in industrial installations of pulp, paper, or wood-based panels
- Pre-treatment (operations such as washing, bleaching, mercerisation) or dyeing of textile fibres or textiles (treatment capacity >10 t/d)
- Tanning of hides and skins (>12 t/d of finished products)
- Disposal or recycling of animal carcases or animal waste (treatment capacity >10 t/d)
- Intensive rearing of poultry or pigs:
  - with more than 40 000 places for poultry;
  - with more than 2 000 places for production pigs (over 30 kg), or
  - with more than 750 places for sows (scrofe).
- Food & Feed Industries

IED: ANNEX I

Industries related to food and feed

- Operating slaughterhouses (carcass production > 50 t/d)
- Treatment and processing of milk only, the quantity of milk received being > 200 t/d (average value on an annual basis).
- Treatment and processing, other than exclusively packaging, of the following raw materials, whether previously processed or unprocessed, intended for the production of food or feed from:
  - only animal raw materials with finished product production >75 t/d;
  - only vegetable raw materials with finished product production capacity >300 t/d or 600 t/d where the installation operates for a period <90 consecutive days in any year;
  - animal and vegetable raw materials, both in combined and separate products, with a finished product production capacity:
    - >75 t/d if A is equal to 10 or more
    - [300- (22,5 × A)] in any other case

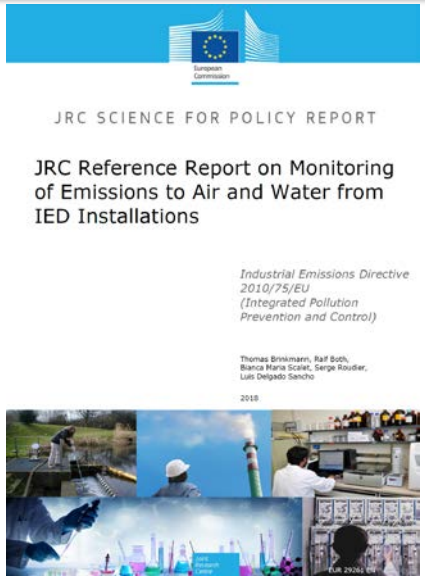
    Where A is the portion of animal material (in % of weight) of the finished product production capacity (excluding packaging)



IED

The permit includes, ao (Art. 12):

- the **sources of emissions** from the installation;
- measures planned to **monitor emissions** into the environment and **emission limits**;



European Commission, "JRC Reference Report on Monitoring of Emissions to Air and Water from IED Installations", 2018

(https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-12/ROM_2018_08_20.pdf)

Odour

- Dynamic olfactometry (EN 13725)
- Field inspection (EN 16841)
- **Electronic sensor systems**
- Odour surveys / odour diaries

PERMIT & BAT

- The European Commission (IPPC Bureau) produces reference containing 'best available techniques' (BAT) for different types of installations: https://eippcb.jrc.ec.europa.eu/reference
- **You need to use BAT** if your operation is an IED installation
- When you apply for an environmental permit you must state whether you're going to follow each BAT that applies to your activity, or propose an alternative. For any BAT you're not going to follow, you must propose an alternative technique.
- **Within 4 years of publication of decisions on BAT conclusions relating to the main activity of an installation**, the competent authority shall ensure that all the permit conditions for the installation concerned are reconsidered and, if necessary, updated to ensure compliance with the Directive, and that **the installation complies with those permit conditions**.

Most recent BAT reference documents for different types of installations mention odours and require the installation to have an **Odour Management Plan**

ODOUR MANAGEMENT PLANT: EXAMPLE FOR REFINERIES

Refineries should have an odour management plan as a well identified part of their environmental management system (see Section 4.15.1.1). The odour management plan should include all of the following elements:

- an odour management strategy;
- protocols for conducting odour monitoring;
- a protocol for response to identified odour events;
- an ongoing odour prevention and elimination programme designed to identify the location, nature, emission and dispersion of on-site odours, to characterise the odours, and to implement elimination and/or reduction measures in relation to these odours;
- an implementation timetable for all actions to be taken within this programme;
- reporting procedures to regularly advise management on the results of the plan;
- a review programme for regularly updating the plan.

Article 8: Non-compliance

In the event of a **breach of the permit conditions**,

a) the operator shall **immediately inform the competent authority**;
b) the operator shall **immediately take the measures** necessary to ensure that compliance is restored within the shortest possible time;
c) the competent authority requires the operator to take **any appropriate complementary measures considered necessary to restore compliance**.

Where the breach of the permit conditions poses an immediate danger to human health or threatens to cause an immediate significant adverse effect upon the environment, and until compliance is restored in accordance with points (b) and (c), **the operation of the installation or relevant part thereof shall be suspended**.

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: WHERE??

- **Emission sources**:
  - **Continuous odour quantification**
  - Continuous evaluation of odour **abatement efficiency** of end-of-pipe treatment systems
  - **Process control**

- **Plant fenceline**:
  - **Real-time identification of critical conditions**
  - Verification of **plausibility of odour detections at receptors**

- **Ambient air/ receptor**:
  - **Direct determination of odour impact/ exposure** (e.g. where dispersion modelling is not applicable)
  - **Recognition of odour provenance** where several sources co-exist (within one plant or different plants)

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: WHERE??

- **Emission sources**:
  - **Co**
  - Co
  - **Pro**
- **Plant f**
  - **Re**
  - Ver
- **Ambie**
  - **Dir**
    not
  - **Re**
    different plants)

Different systems, training, and data pre-treatment and processing algorithms may be required according to the specific application and to the desired output

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: HOW??

WORKFLOW:

1. **Study of the process and identification of main odour emission sources**
2. **E-nose training**
3. **Acquisition of monitoring data and data processing**
4. **Interpretation of monitoring results**

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: HOW??

1. **Study of the process and identification of main odour emission sources**
   a) **Study of plant permit and other technical documents**
   b) **Plant inspection**
   c) **Olfactometric characterization of emission sources and calculation of odour emission rates**
   d) **Dispersion modelling (optional)**

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: HOW??

1. Study of the process and identification of main odour emission sources

   a) **Study of plant permit and other technical documents**

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   d) Dispersion modelling (optional)

PLANT PERMIT

A permit shall include a descriptior

(a) the **installation and its activitie**

(b) the **raw and auxiliary materials** ated by the installation;

(c) the **sources of emissions** from t

(d) the **conditions of the site** of the

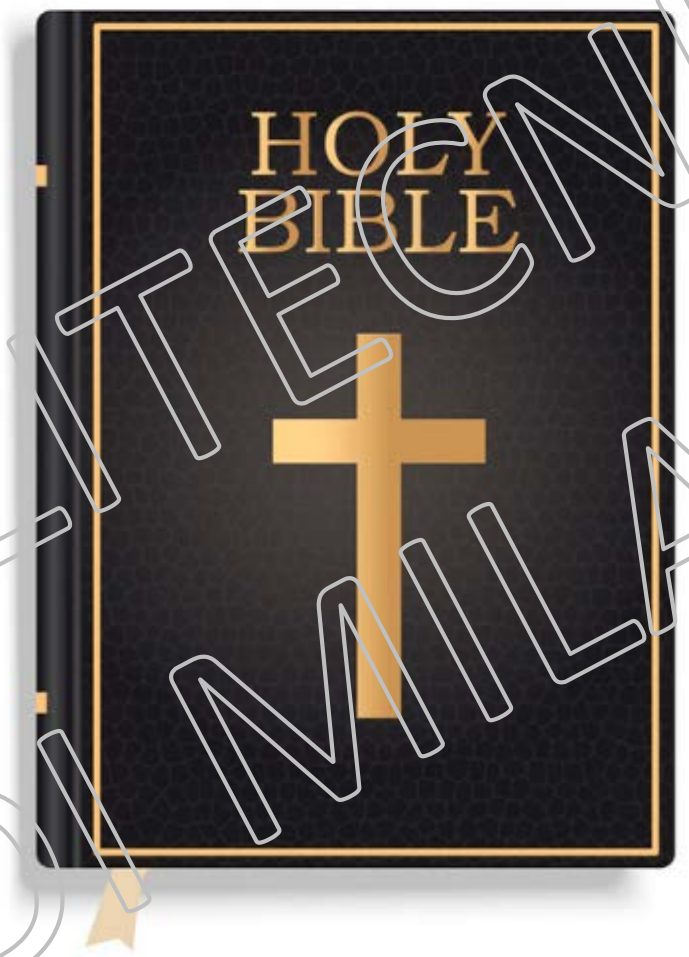
(f) the **nature and quantities of for** medium as well as identification of significant effects of the emissions

(g) the proposed **technology and o** **ns** from the installation;

(h) measures for the **prevention, p** **ste** generated by the installation;

(j) measures planned to **monitor e**

(k) the main **alternatives to the pr** ed by the applicant in outline.



OTHER TECHNICAL DOCUMENTS

- Technical documents regarding installed abatement systems
- Previous monitoring reports (olfactometric analyses if available, or chemical analyses)
- Environmental impact studies by dispersion modelling (if available)
- List of nearest receptors
- History of odour complaints
- …

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: HOW??

1. Study of the process and identification of main odour emission sources
   a) Study of plant permit and other technical documents
   b) **Plant inspection**
   c) Olfactometric characterization of emission sources and calculation of odour emission rates
   d) Dispersion modelling (optional)

PLANT INSPECTION

- Position and availability of sampling points (for training)
- Effective status of the plant (conformity to descriptions in the permit)
- Real dimensions of sources
- Air suction system
- Unforeseen (diffuse) emissions (e.g., openings, vents, etc.)

Inspection report with description of emission sources and definition of sampling strategy

Keep eyes (and noses!) opened, and ask questions!!

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: HOW??

1. Study of the process and identification of main odour emission sources

   a) Study of plant permit and other technical documents

   b) Plant inspection

   c) **Olfactometric characterization of emission sources and calculation of odour emission rates**

   d) Dispersion modelling (optional)

QUANTIFICATION OF EMISSIONS

"SIMPLE" SOURCES

- Point (e.g. stacks)
- Active surfaces (e.g. biofilters)

$$\mathbf{OER} = Q_{20°C} \cdot C_{od} = \left[\frac{ou_E}{s}\right]$$

NORMAL CONDITIONS FOR OLFACTOMETRY:

- Temperature = 20°C
- Pressure = 1 atm
- Wet flux

COMPLEX SOURCES

- Still liquid surfaces
- Aerated liquid surfaces
- Buildings
- Storage tanks
- Porous solid heaps
- Landfills

OER??

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: HOW??

1. Study of the process and identification of main odour emission sources

   a) Study of plant permit and other technical documents

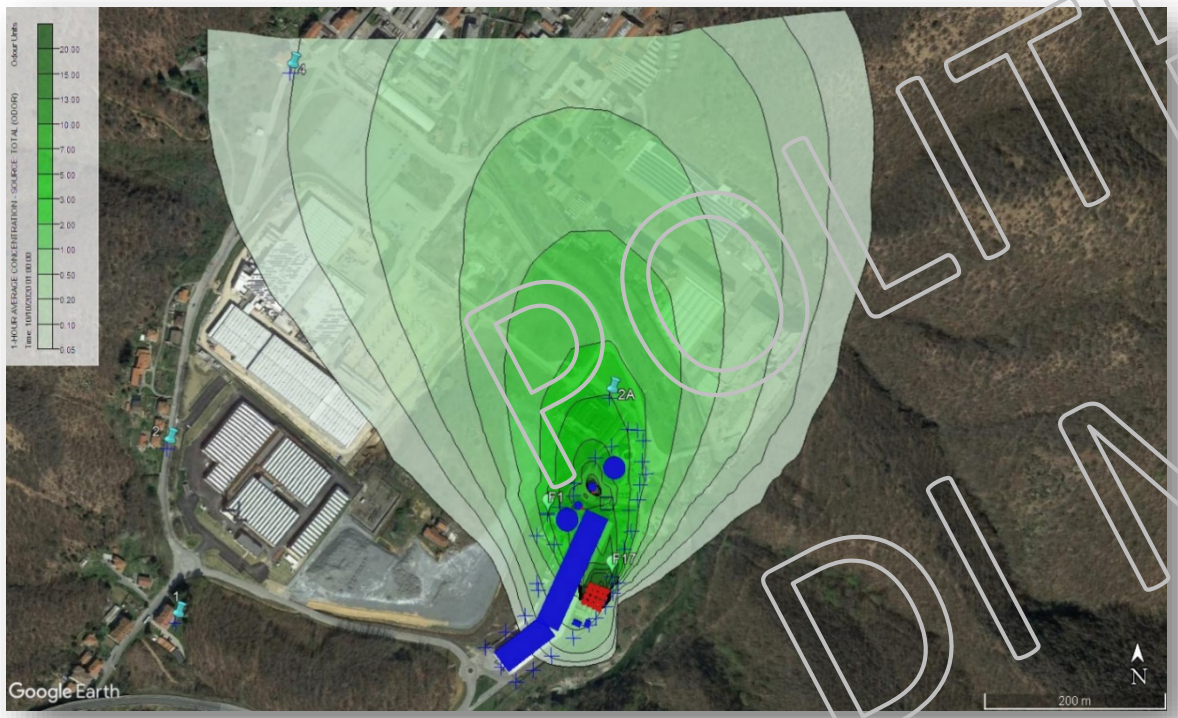
   b) Plant inspection

   c) Olfactometric characterization of emission sources and calculation of odour emission rates

   d) **Dispersion modelling (optional)**

DISPERSION MODELLING

- Identification of prevailing wind directions and of most impacted receptors
- Choice of the most suitable installation point(s)



2. E-nose training

a) Sampling

b) Olfactometric analysis

c) Dilution

d) Analysis by e-nose for creation of training dataset

E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING: HOW??

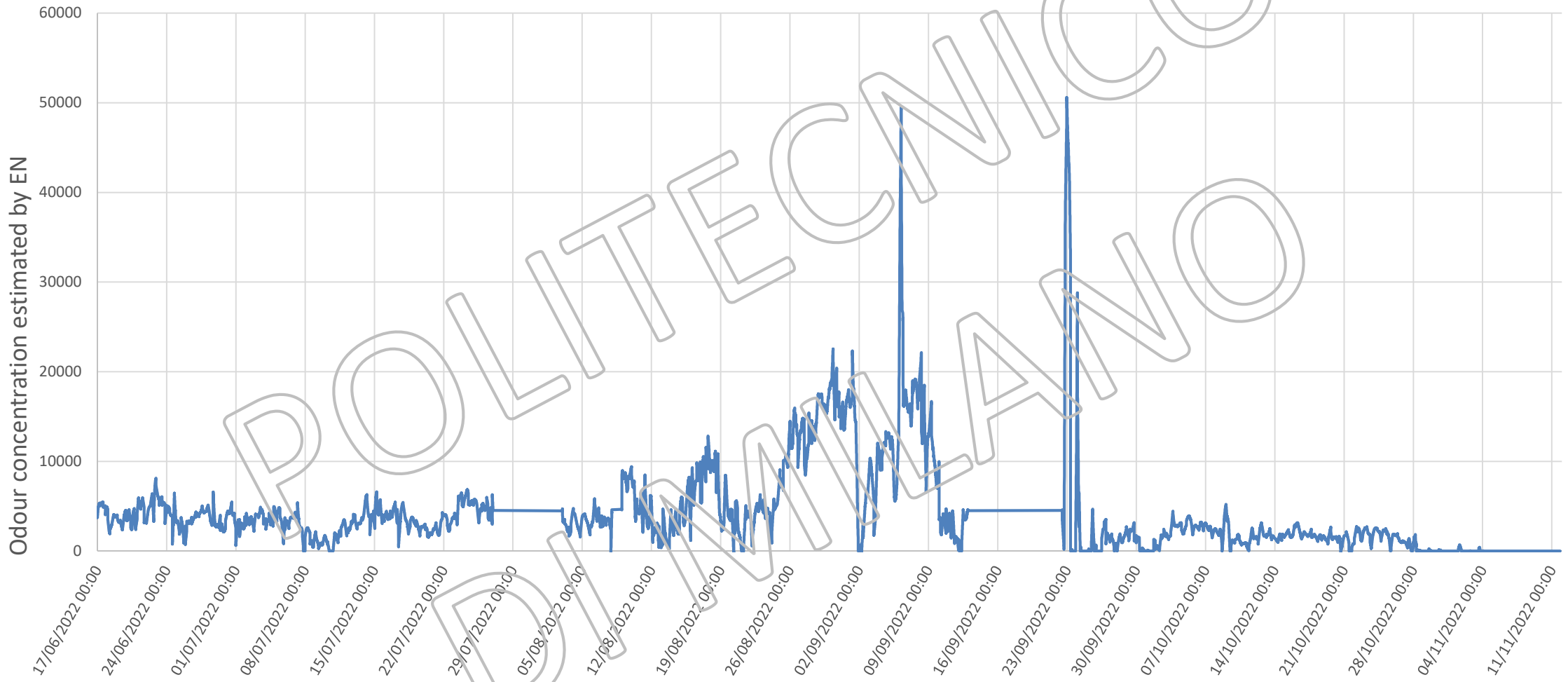
WORKFLOW:

1. **Study of the process and identification of main odour emission sources**
2. **E-nose training**
3. **Acquisition of monitoring data and data processing**
4. **Interpretation of monitoring results**

RESEARCH QUESTION!!!

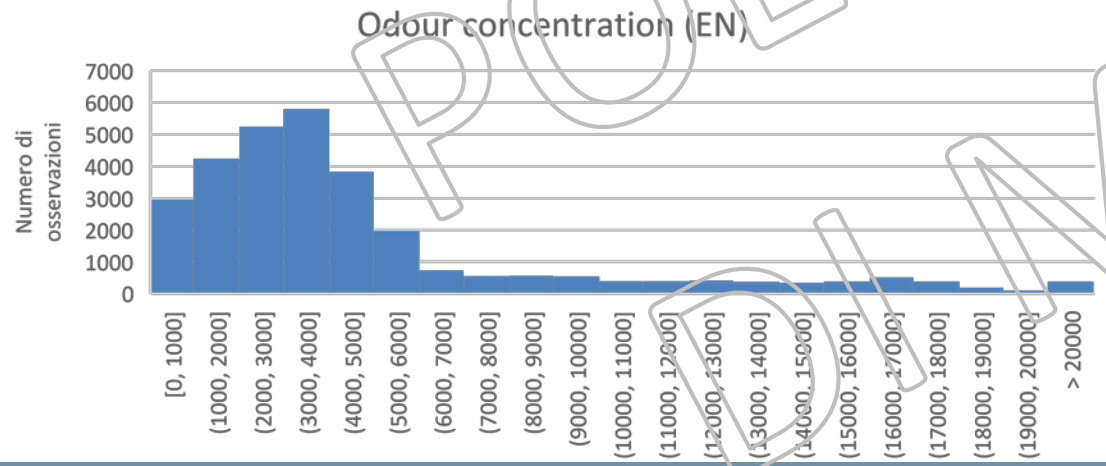
- What is the impact of the plant (on a given receptor)?
- Which is the most impacting source?
- Which is a suitable odour concentration threshold to prevent odour events outside the plant?
- …

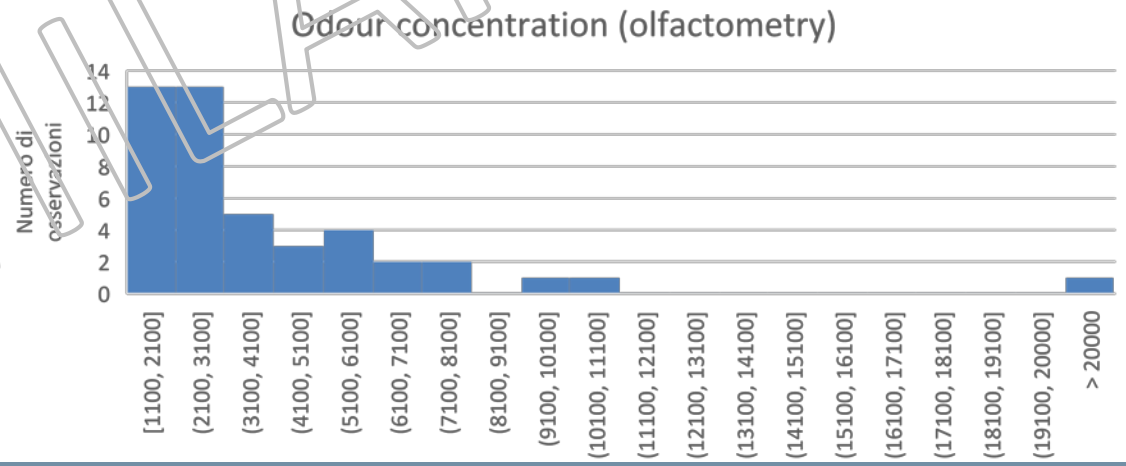
EXAMPLE: IDENTIFICATION OF ODOUR PEAKS AT THE INLET OF AN ABATEMENT SYSTEM



EXAMPLE: IDENTIFICATION OF ODOUR PEAKS AT THE INLET OF AN ABATEMENT SYSTEM

Percentile	Odour concentration estimated by EN	Reference odour concentration (olfactometry) [ou_E/m^3]
50	< 3400	< 2900
60	< 4000	< 3300
70	< 4700	< 4300
80	< 6200	< 5800
85	< 8700	< 6900
90	< 12100	< 7300
95	< 16000	< 11000





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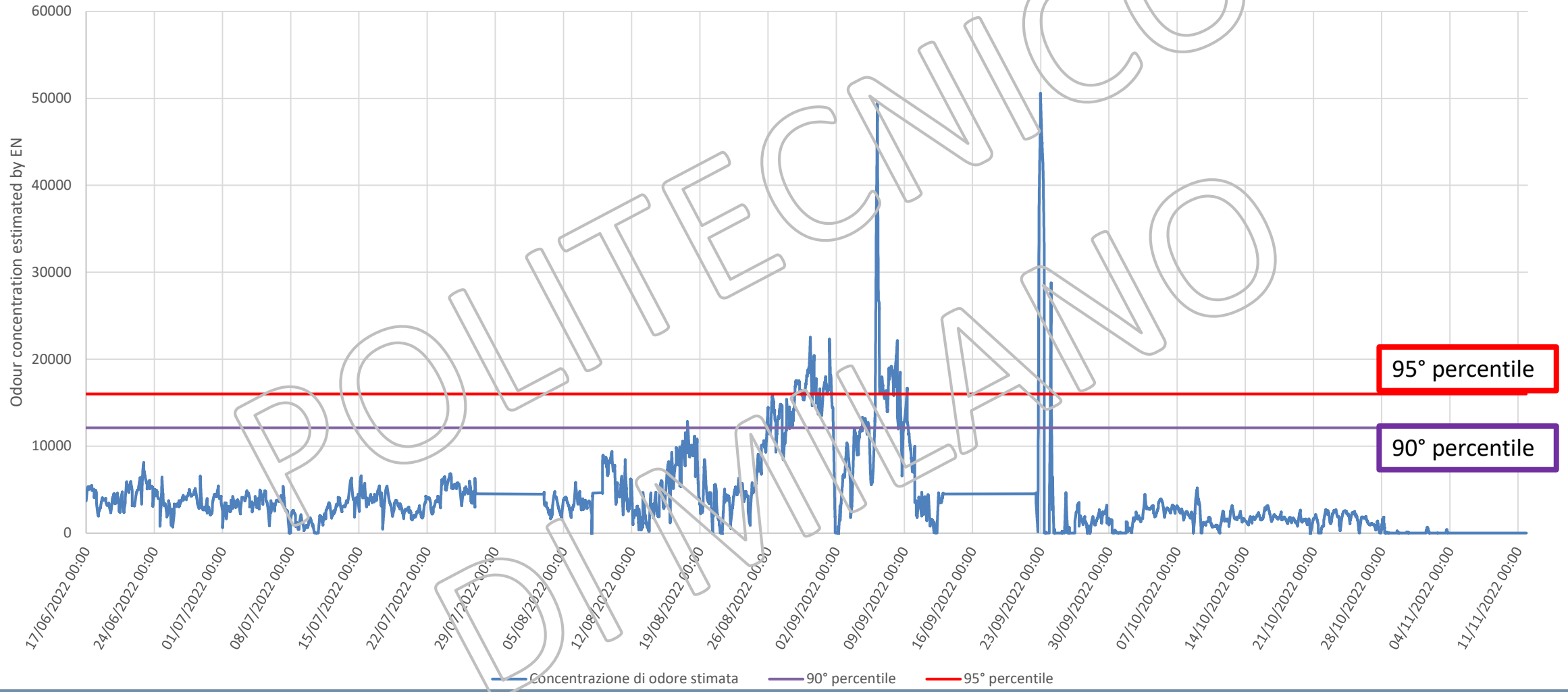

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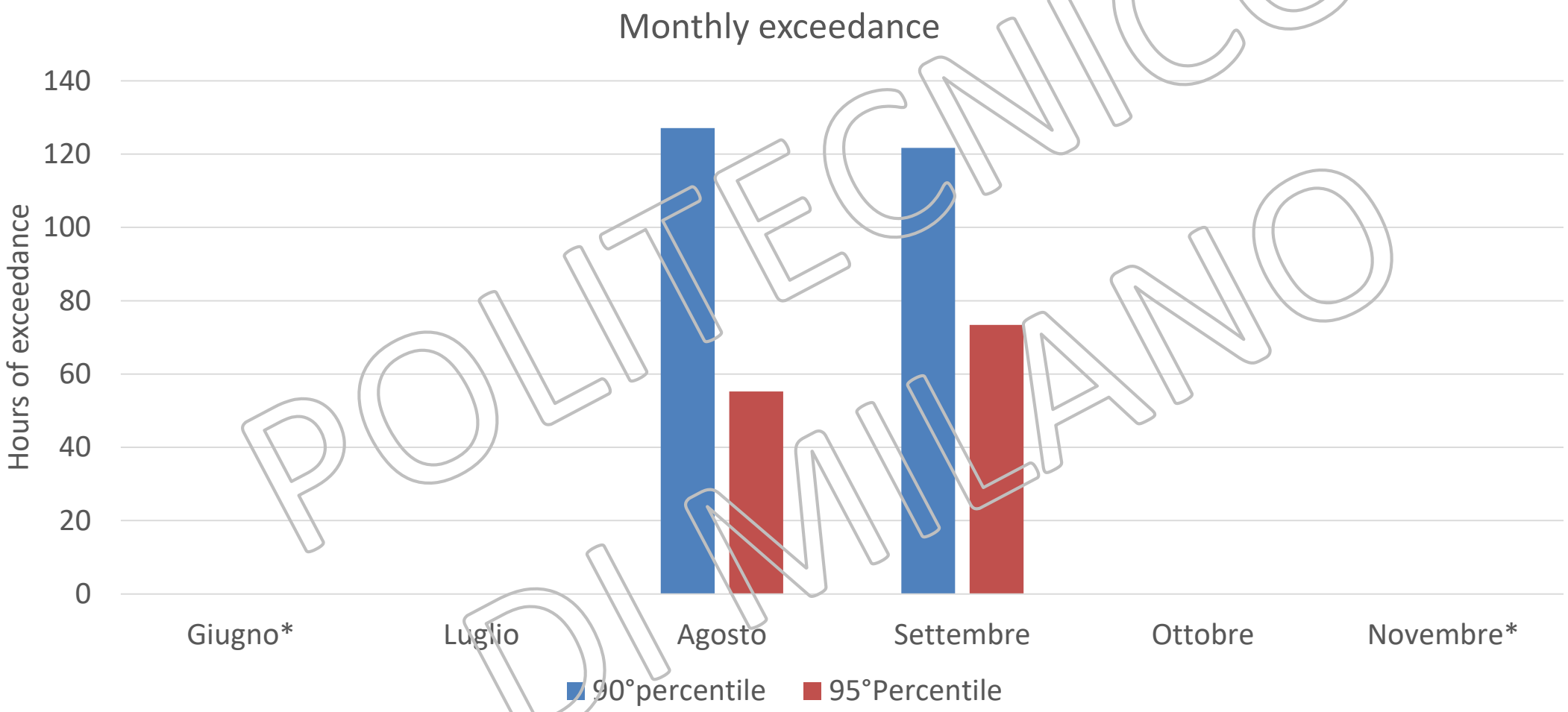
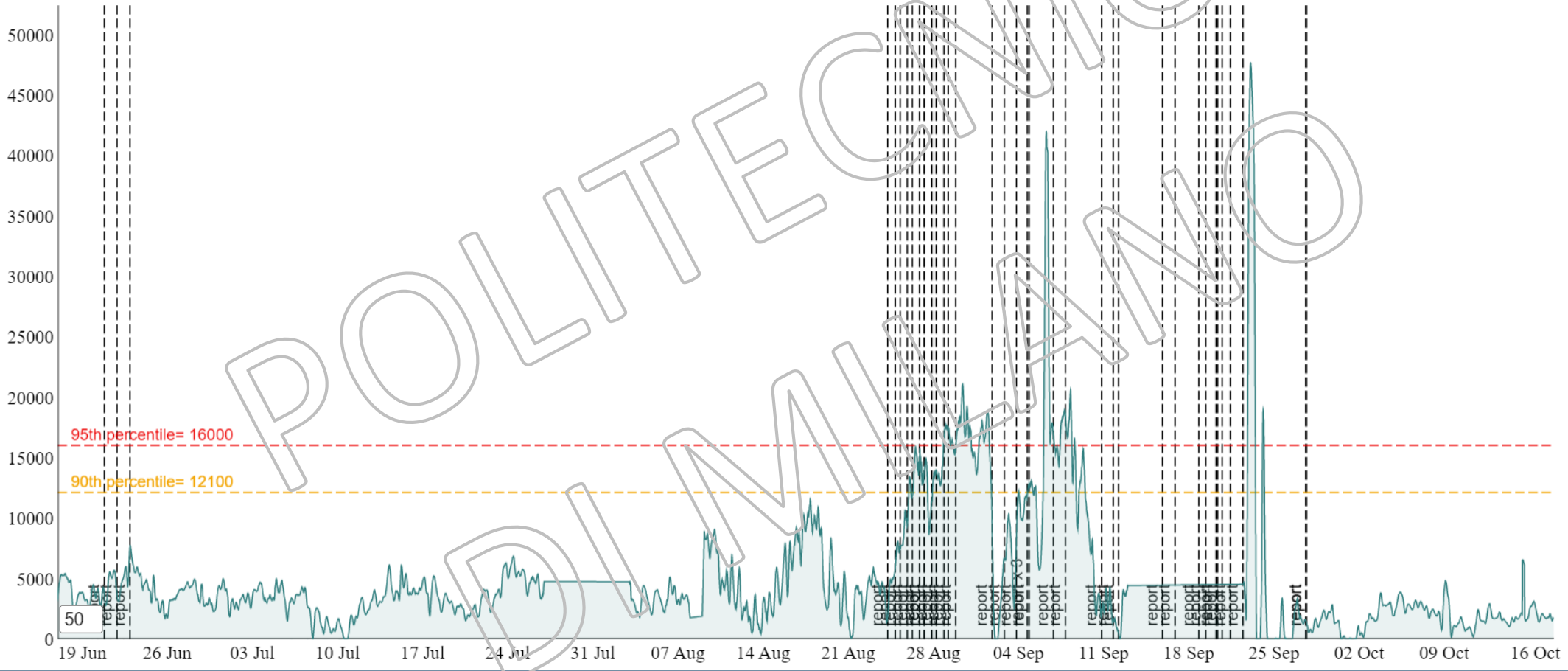


EXAMPLE: IDENTIFICATION OF ODOUR PEAKS AT THE INLET OF AN ABATEMENT SYSTEM

Correlation with citizens' odour complaints



EXAMPLE: IDENTIFICATION OF ODOUR PEAKS AT THE INLET OF AN ABATEMENT SYSTEM

Results of the study:

- Real-time measurement of concentration at the system inlet
- Identification of peaks and definition of thresholds for the activation of sampling systems
- Investigation of the reasons for the variability of the odour concentration (in progress)

CURRENT CHALLENGES AND FUTURE PERSPECTIVES

1. Standardization
2. Odour quantification
3. Drift correction/ compensation
4. Compensation of interferences (non-odorous gases)
5. Combination of e-nose outputs with meteorological data/ dispersion models

1. STANDARDIZATION

E-noses are no longer research objects, but are gaining a **legal value**

There is an urgent need for **standardization** and for **quality protocols** for **performance verification**[1]

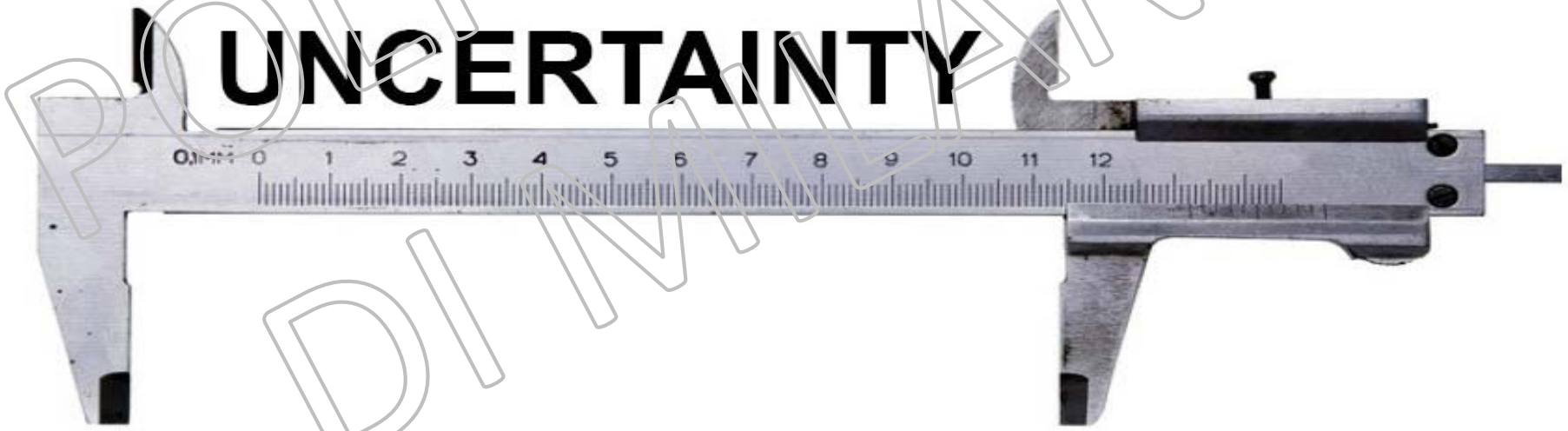
[1] Cipriano, D., & Capelli, L. (2019). Evolution of electronic noses from research objects to engineered environmental odour monitoring systems: A review of standardization approaches. Biosensors, 9(2), 75.

1. STANDARDIZATION

- Standardization approaches do not deal with the instrument hardware, but define performance requirements
- Distinction between detection/ classification/ quantification
- Synthetic vs real odours for testing

2. ODOUR QUANTIFICATION: PROBLEMS

- Development of accurate models for predicting odour concentrations
- Compensation of interferences (e.g., humidity, non-odorous gases)
- Comparison with the reference method



3. DRIFT AND ITS CONSEQUENCES

DRIFT = Change of sensor responses over time

Decrease of model performance

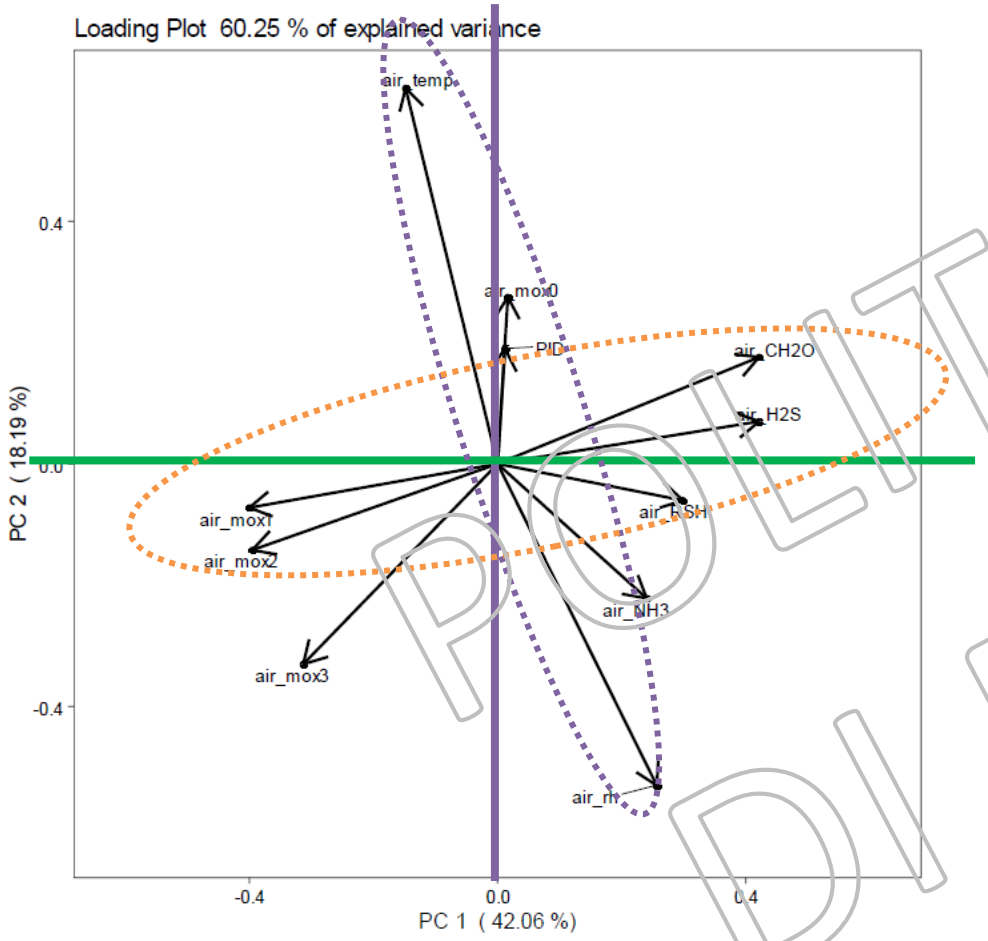
Need for recurrent calibration

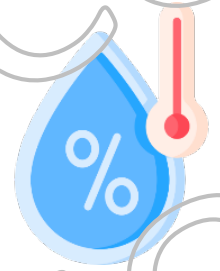
High costs and time loss

4. COMPENSATION OF INTERFERENCES (NON-ODOROUS GASES)

- Gas sensors have **undesired cross-sensitivities** (e.g., temperature, humidity, non-odorous gases), making that their **responses are not always correlated with the odour concentration**
- Things are not necessarily better using “specific” electrochemical sensors

4. INVESTIGATION OF POSSIBLE CAUSES FOR THE INTERFERENCE

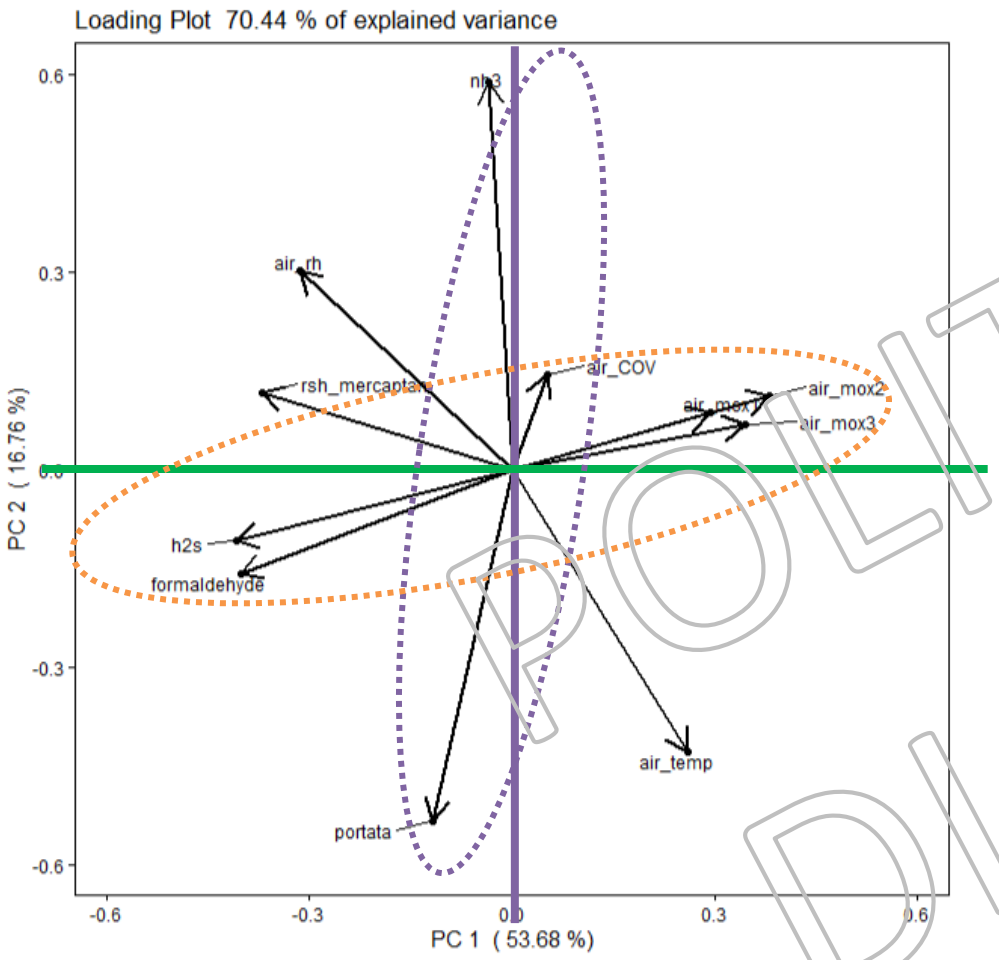


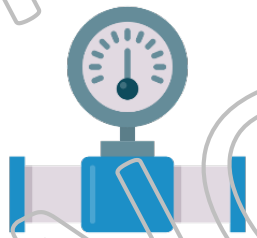


No correlation of the sensor responses with the variations of humidity and temperature

Humidity and temperature are not the main causes of the sensors' oscillations

4. INVESTIGATION OF POSSIBLE CAUSES FOR THE INTERFERENCE

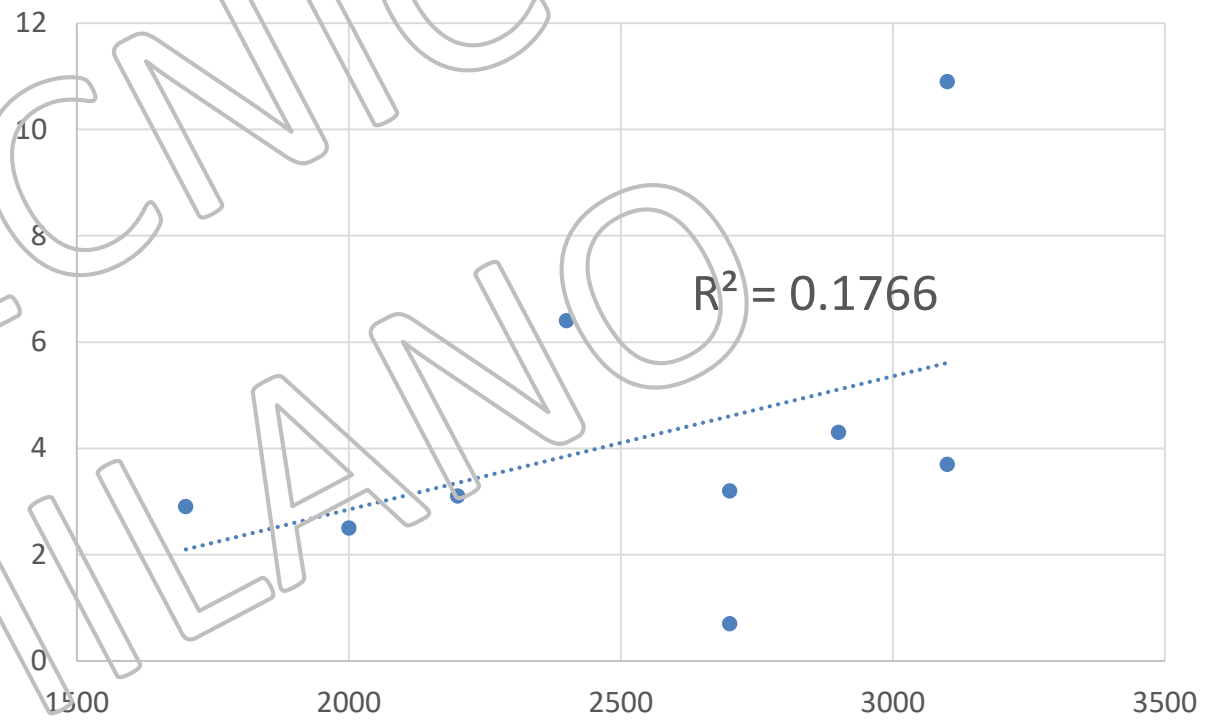




Also the variations of the flowrate of wastewater entering the plant is not the cause of the oscillating sensors' responses

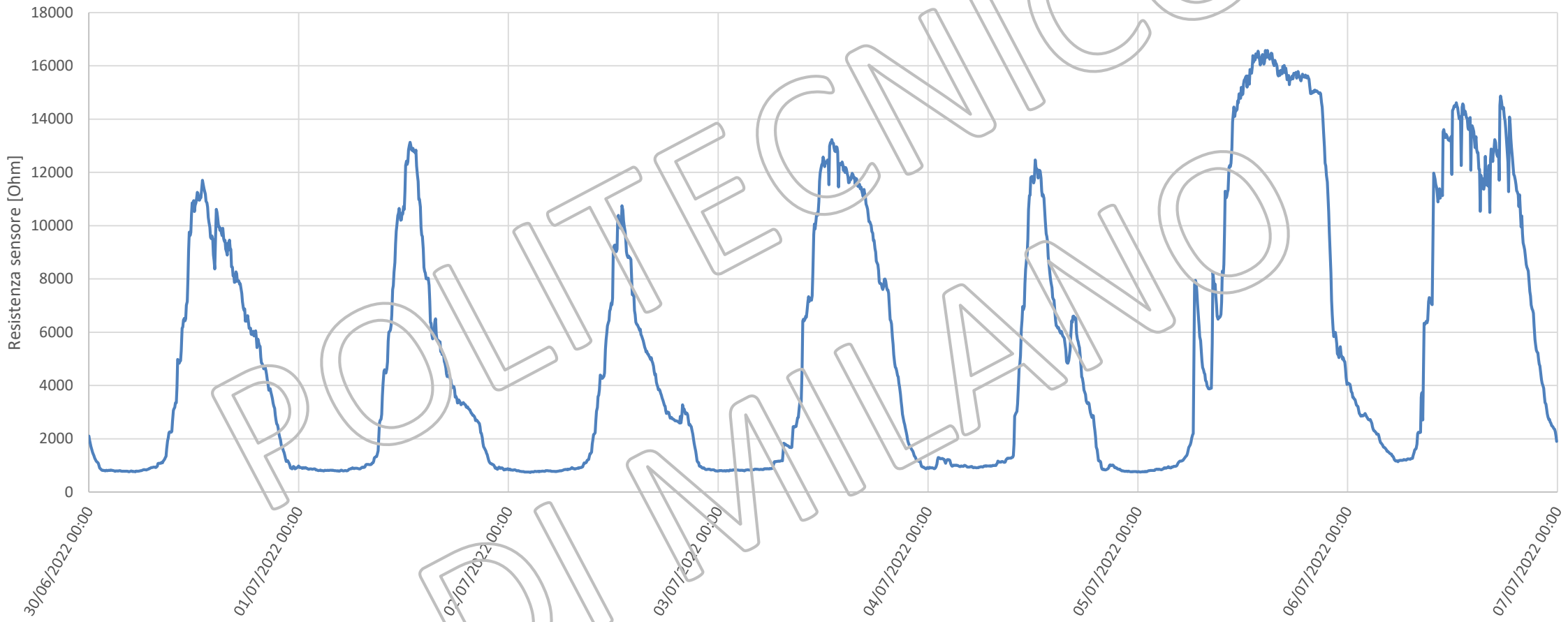
4. INVESTIGATION OF POSSIBLE CAUSES FOR THE INTERFERENCE

Date	Hour	Odour concentration (ou/m3)	H2S concentration (ppm)
12/9	10:43	**3100**	**3.7**
12/9	11:51	**2200**	**3.1**
12/9	12:40	**2700**	**0.7**
12/9	14:13	**2000**	**2.5**
12/9	15:40	**1700**	**2.9**
12/9	17:01	**2700**	**3.2**
12/9	17:38	**2900**	**4.3**
13/9	01:00	**3100**	**10.9**
13/9	08:22	**2400**	**6.4**



No correlation between H2S sensor response and odour concentration, either!!!

4. SENSORS' RESPONSE NORMALIZATION



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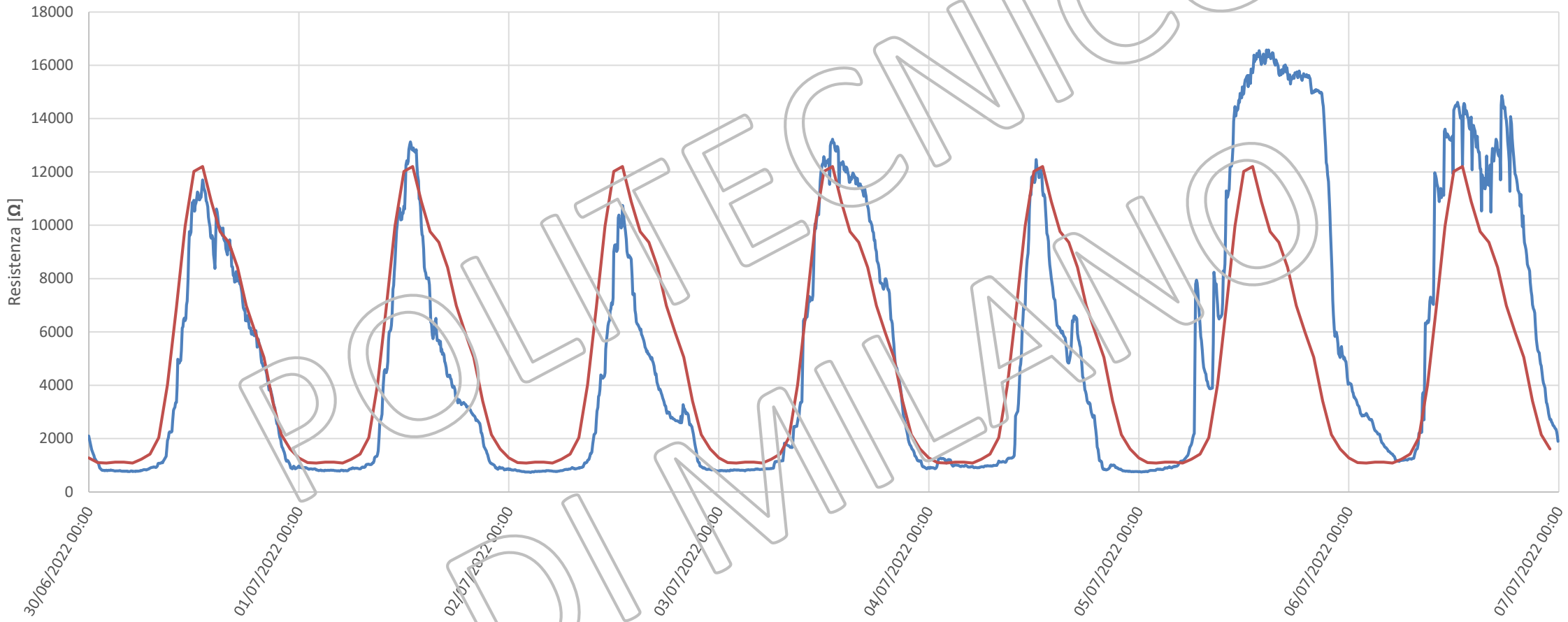

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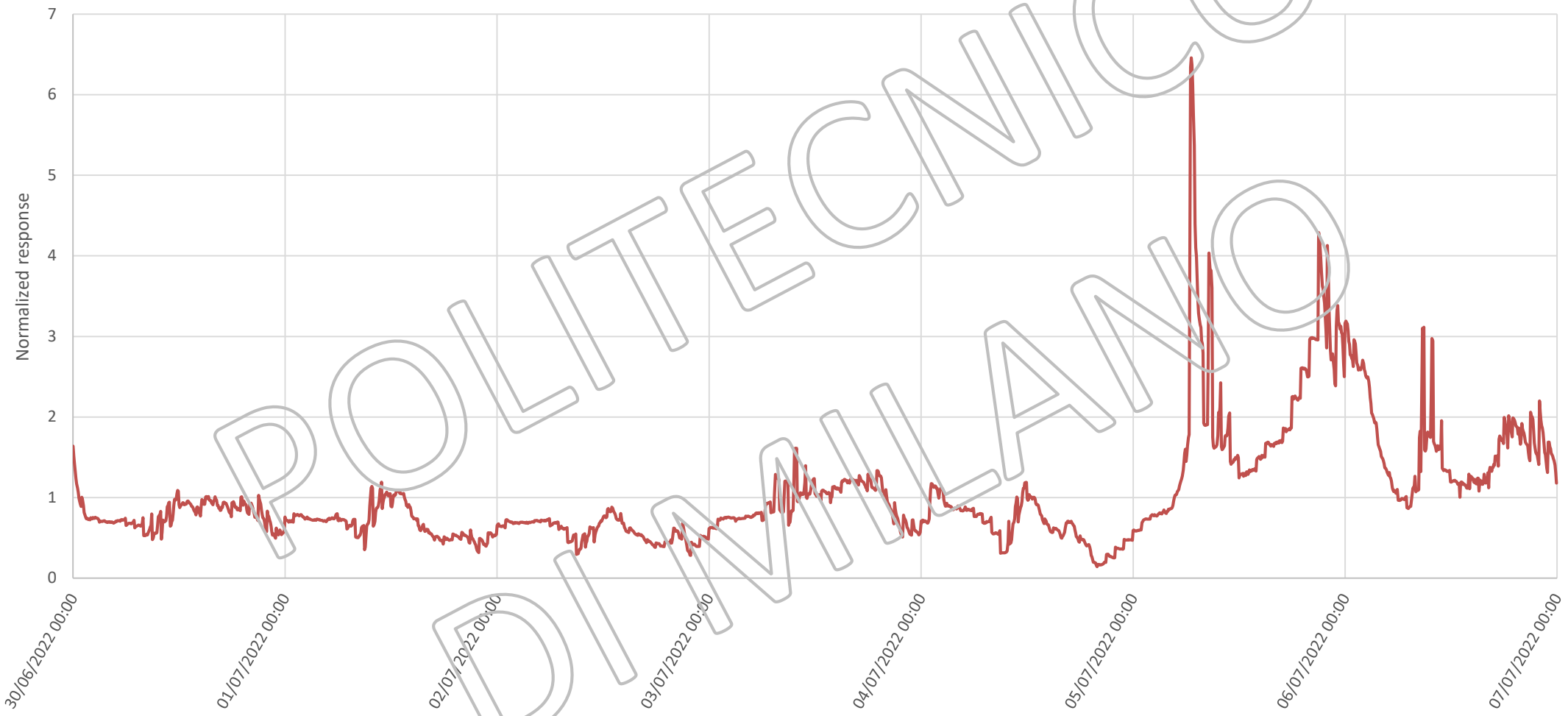


4. EXTERNAL VALIDATION

Test sample no.	Odour concentr ation estimated by e-Nose	Reference odour concentration (olfactometry) (ou_E/m^3)	Intervallo di confidenza olfattometria 95% (ou_E/m^3)
1	1762	1650	700 ÷ 3000
2	1617	3650	1600 ÷ 6700
3	658	330	140 ÷ 600
4	268	480	200 ÷ 900
5	2293	700	300 ÷ 1300
6	1338	1450	630 ÷ 2700
7	1762	1650	720 ÷3000
8	2411	650	280 ÷1200
9	2557	2450	1100 ÷ 4500
10	8529	11000	4800 ÷ 20000
11	6200	6900	3000 ÷13000
12	28377	10000	4400 ÷18000
13	49605	30000	13000 ÷ 55000

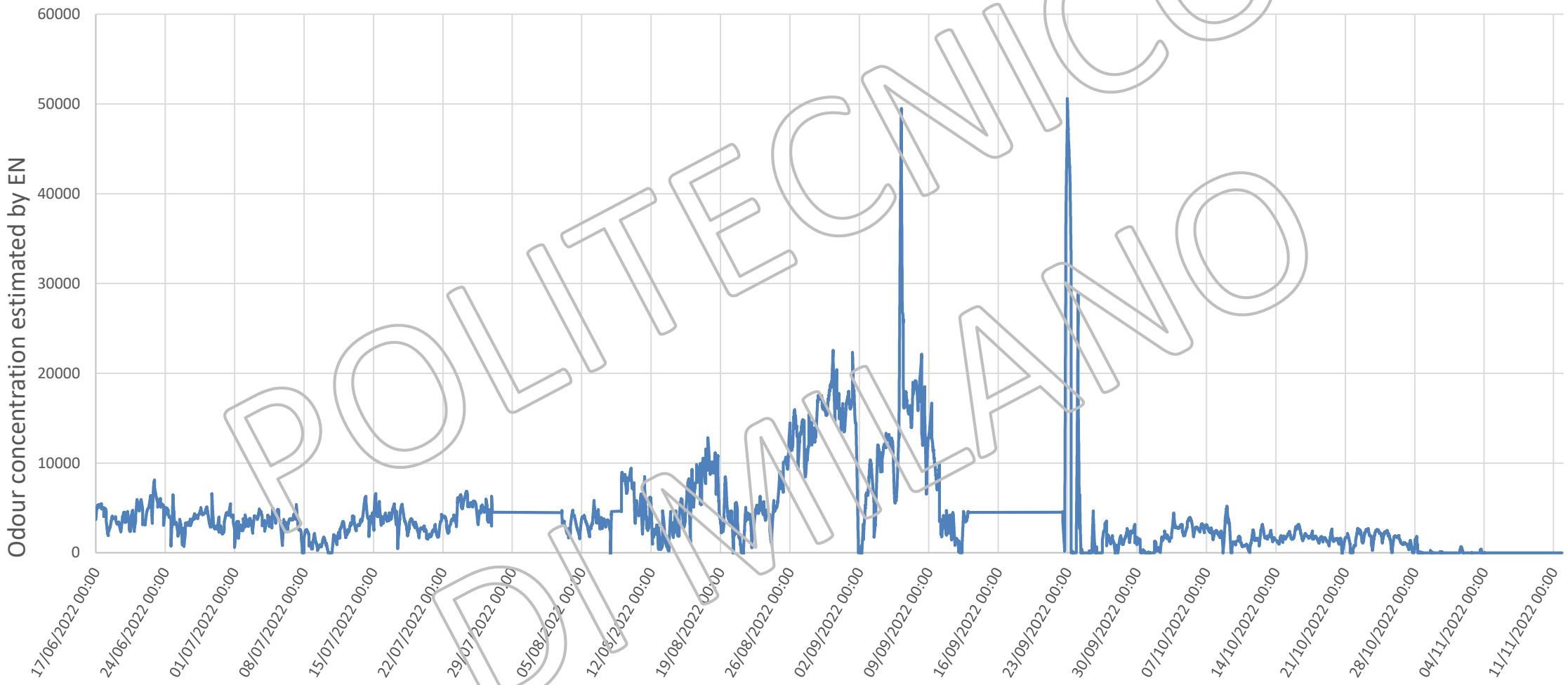
Training Accuracy:

85 % ($CI_{95\%}$ 76 – 94 %)

Test accuracy:

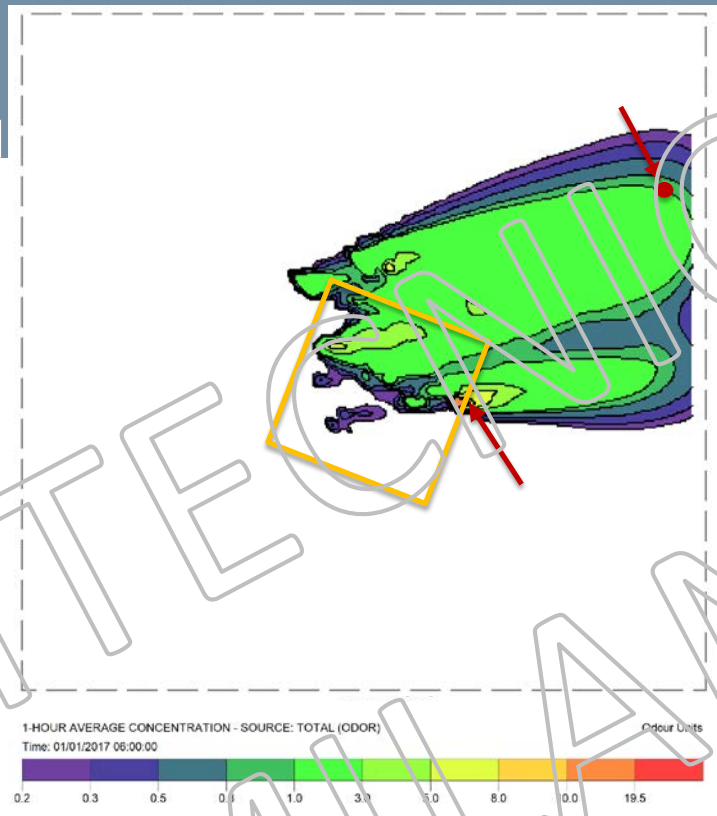
69 % ($CI_{95\%}$ 39 – 91 %)

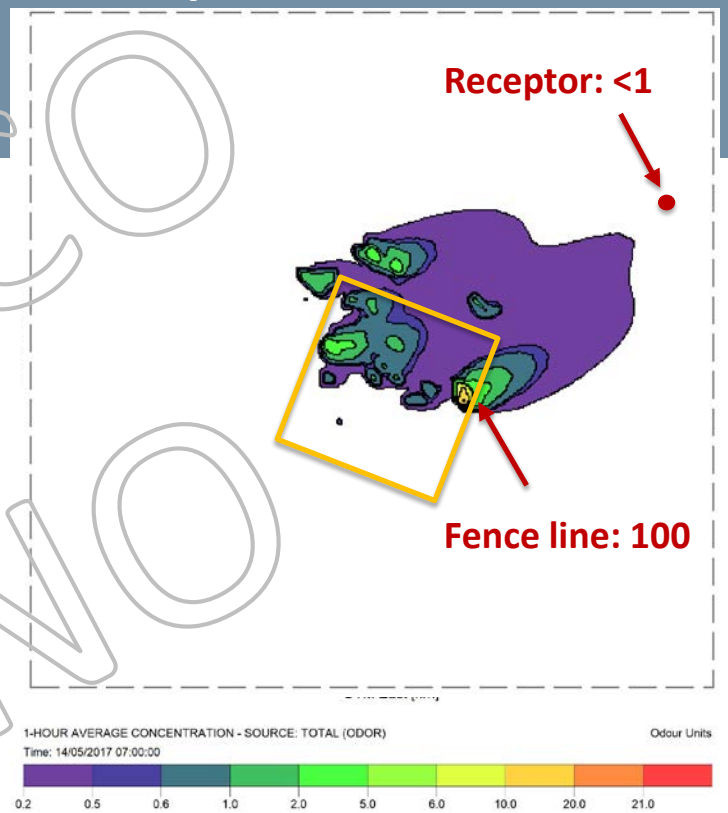
4. MONITORING RESULTS



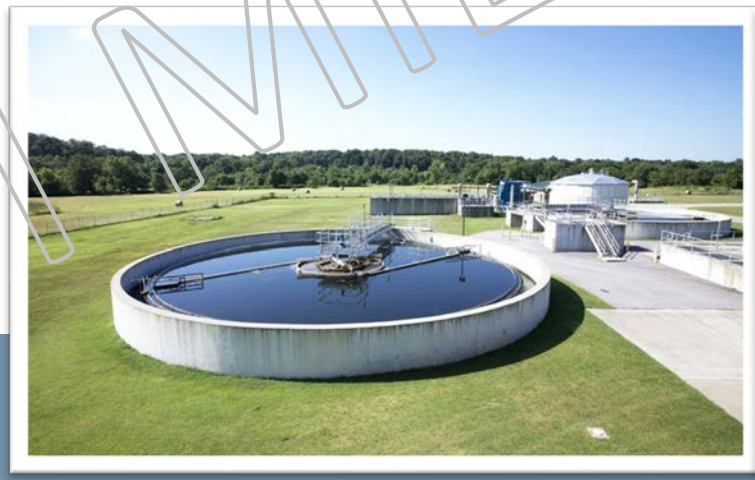
5. COMBINATION OF E-NOSE OUTPUTS WITH METEOROLOGICAL DATA/ DISPERSION MODELS

- Development of fenceline **monitoring systems with variable alarm thresholds** correlated with the probability of odour perceptions at receptors





- **Indirect estimation of odour emission rates** of complex sources



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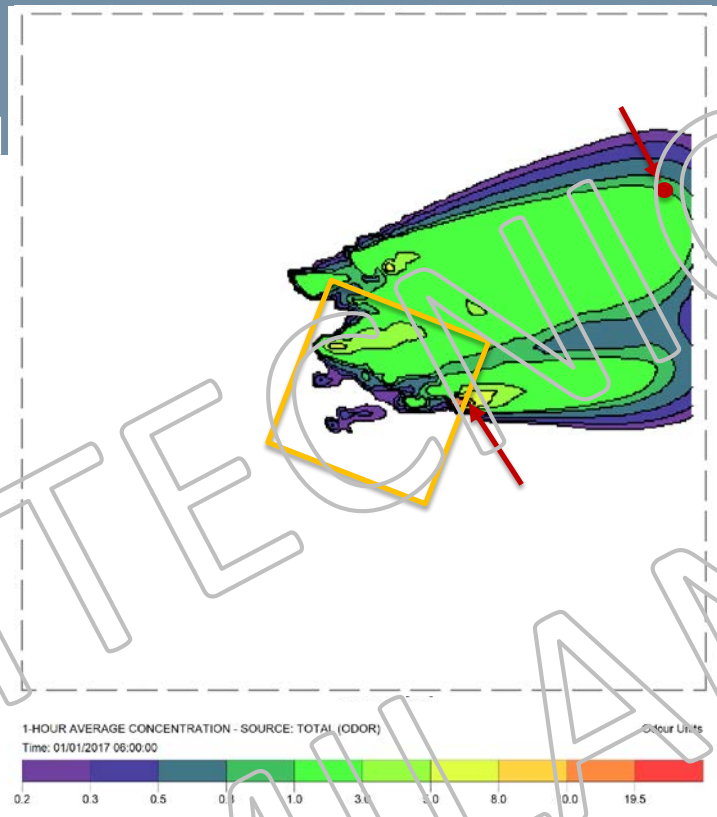
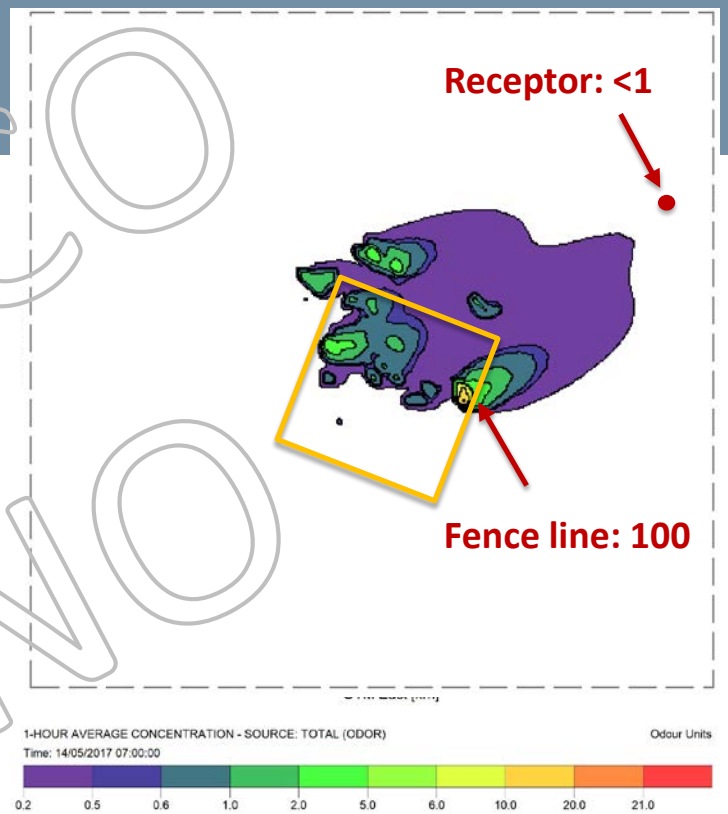


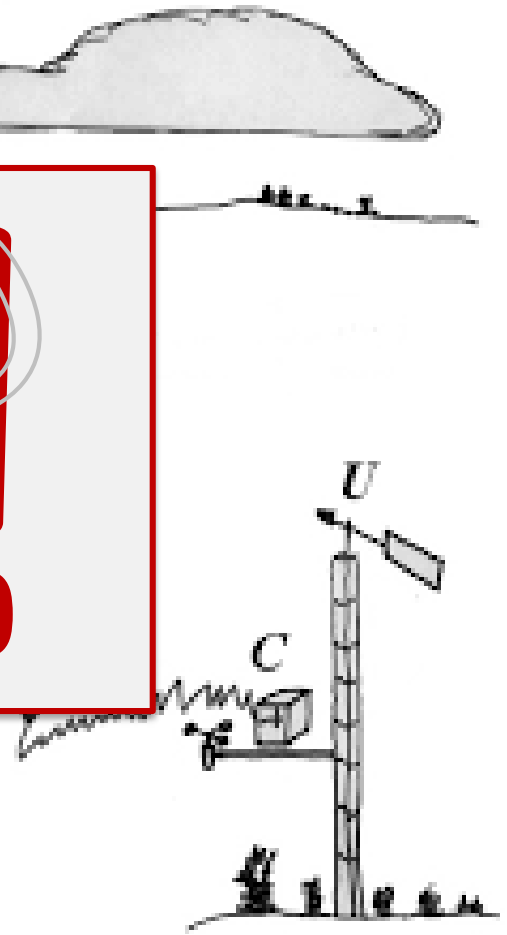


- **Indirect estimation of odour emission rates** of complex sources

- Micrometeorological methods combine **local micrometeorological conditions** and **downwind conce**
  vertic

! COMPLEX METHODS !

Th
implementation has become **more reliable and affordable** in terms of cost



5. CURRENT LIMITATIONS

- The **main limitation** to its application to the direct estimation of odour fluxes is related to the **resolution and accuracy of the odour concentration measurements:** specific evaluations are needed!
- **Odour concentration measurements downwind and at some distance from the source are generally not feasible,** making reverse dispersion modelling scarcely reliable.
- The **Gradient Method** could potentially be applied for the indirect estimation of odour emissions from complex sources.
- A **standardisation of the experimental facilities** needed for the implementation of such methods is missing, especially regarding their application to VOC measurements.

[1] Lotesoriere, B. J., Invernizzi, M., Panzitta, A., Uvezzi, G., Sozzi, R., Sironi, S., & Capelli, L. (2022). Micrometeorological Methods for the Indirect Estimation of Odorous Emissions. Critical Reviews in Analytical Chemistry, 1-30.

CONCLUSIONS: E-NOSES FOR ENVIRONMENTAL ODOUR MONITORING

E-noses are **essential tools to complement other (sensorial) odour measurement techniques**, especially (but not exclusively) where continuous monitoring is needed

- **Accuracy, reliability, and stability** over time are still an open issue
- **Standardisation and quality protocols** are needed for their use as air quality monitoring tools
- A **high degree of customization** is still required for environmental applications
- There is still a lot of research work to be done…

THANK YOU!!

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