Electronic noses for the real time assessment of odour concentration: example of the monitoring of odour emissions from a landfill

Carmen Bax carmen.bax@polimi.it, *Beatrice Julia Lotesoriere, Laura Capelli*

Politecnico di Milano, Milano

Riassunto

I nasi elettronici (o IOMS) rappresentano l'unico strumento disponibile per il monitoraggio continuo degli odori, consentendo la valutazione diretta dell'impatto olfattivo, anche in caso di sorgenti complesse. Un'interessante prospettiva di sviluppo degli IOMS è il monitoraggio real-time del processo. A tal fine, l'IOMS deve essere in grado di fornire una misurazione continua, rapida e accurata della concentrazione di odore. L'approccio attualmente utilizzato per la quantificazione degli odori mediante IOMS prevede la costruzione di modelli di regressione semplificati, che non considerano la classificazione. Tali modelli sono spesso inefficaci: le risposte dell'IOMS a campioni odorigeni aventi la stessa concentrazione, ma rappresentativi di sorgenti diverse, possono differire in modo significativo. Il presente lavoro descrive un caso studio riguardante l'applicazione di due IOMS al monitoraggio degli odori da una discarica. Il lavoro è incentrato sullo sviluppo di un nuovo modello per la stima della concentrazione al confine di impianto, basato sulla costruzione di modelli di regressione specifici per le varie sorgenti odorigene della discarica, e il protocollo sperimentale adottato per l'addestramento e la verifica prestazionale in campo.

Abstract

Electronic noses currently represent the only tool available for the continuous monitoring of odours, enabling the direct assessment of the odour impact, even in case of complex odour sources. An interesting development perspective of IOMS is real-time process monitoring. For this purpose, the IOMS must provide a continuous, fast and accurate measurement of the odour concentration. The approach that is currently used for odour quantification by IOMS involves the construction of simplified regression models, which do not consider the odour class previous to regression. Consequently, such models are often ineffective: IOMS responses to odorous samples having the same concentration, but representative of different sources, may differ significantly. The present work describes a case study regarding the application of two IOMS to the monitoring of odours from a landfill. The work focuses on the development of a new approach for the estimation of odour concentration by IOMS at the plant fenceline, based on the construction of specific regression models for the various landfill odour sources, and describes the experimental protocol involved for e-nose training and performance verification in the field.

1.Introduction

Electronic noses currently represent the only tool available for the continuous monitoring of odours [1-3], enabling the direct assessment of the odour impact, even in case of complex odour sources [4]. These include landfills, for which traditional "hood" sampling methods have already been proven ineffective for measuring methane and/or odour fluxes [5]. In such cases, the capability of electronic noses to characterize ambient air without requiring a minute characterization of the odour source [6] becomes particularly useful, and several examples of applications have been described in the recent scientific literature [4, 7-8]. In general, e-noses are installed at receptors to provide a continuous characterization of ambient air. The qualitative information collected during the monitoring period are generally used to assess the detection frequency of odours from the plant under exam, which can be interpreted as the odour impact at the specific monitoring site. This also allows to identify the most critical odour sources. An interesting development perspective of IOMS is the possibility of using them for the real-time monitoring of emission at the plant fenceline, thereby setting "warning" thresholds to promptly identify plant malfunctions and thus intervene to limit odour emissions that might result in odour events at the receptor. Some scientific papers have already proposed the adoption of IOMS for odour quantification [9-11]. However, the most common approach used for building quantification models for e-noses involves simplified regression algorithms, which neglect the classification of the detected odours. Consequently, such models are often poorly accurate, since the responses of IOMS to odorous samples having the same odour concentration, but representative of different sources, may differ significantly. This paper proposes a new approach for the estimation of odour concentration by IOMS, which is based on specific regression models for each odour source of the plant under examination and involves as first step the classification of unknown samples. To do this, this paper describes a case study related to the monitoring of odours from a landfill carried out by two e-noses, i.e. the WT1 (RUBIX) and the EOS507F 8SACMI), installed at plant fenceline and a receptor.

2.Materials and Methods

2.1.Electronic noses

Two e-noses were used for the present work. The EOS507F is equipped with 6 MOS gas sensors, and automatic systems for humidity regulation and realization of reference air (non-odorous air) [12]. The WT1 is an outdoor device for fenceline monitoring of odours and air pollutants, equipped with 2 electrochemical cells for H_2S and NH_3, and 4 MOS sensors (i.e. RIX 102-MOS-Amine, RIX 103-MOS-Amine, RIX 104-MOS-Air, RIX 105-MOS-VOC).

2.2.Description of the selected case study

The selected case study entails the monitoring of odours from a landfill for non-hazardous waste. In particular, the two e-noses were used in a complementary way. The EOS507F was installed at a receptor located about 2 km South of the landfill, to analyse the ambient air continuously, detect odours, and recognize their provenance. The WT1 was installed at the landfill fenceline along the same direction to detect, classify and quantify odours, with the purpose of confirming the EOS507F detections at the receptor, and explore the possibility to identify “warning” odour concentrations levels at the fenceline, which might be associated with odour events at the receptor. The choice of the monitoring sites was based on the analysis of meteorological conditions of the area, which highlighted the existence of a prevalent wind blowing from North to South, thus favouring the detection of odours from the landfill at the receptor. The landfill monitoring lasted about 20 days.

2.3.E-nose training

The training consists in the creation of the Training Set (TS), which will be used by the IOMS as a reference for the classification of the ambient air that is analysed at the receptor and at the fenceline, and the estimation of the odour concentration at the fenceline [4]. For the specific case, the training involved the collection of samples representative of the main landfill odour sources, which are: the fresh waste disposal and pre-treatment, the landfill gas emitted from the landfill surface, and the leachate collection tanks [13,14]. Then, samples were presented to the e-noses for building the TS. The olfactometry campaigns were carried out in different days, with the purpose of including in the TS the intrinsic variability of the landfill odour sources. Samples collected at the sources were characterized by means of dynamic olfactometry [15] to determine their odour concentration and to evaluate the dilution factors to be applied before presenting the samples to the IOMS to build the training set (TS). Based on their odour concentrations, landfill samples were diluted and presented to the e-noses at increasing odour concentrations to assess the Lower Detection Limit (LDL) towards the main landfill odours [4]. The combination of the instrument LDL and the characteristics of the monitoring sites (i.e., the distance from the odour sources) allowed to define the odour concentration ranges to be considered for training the instruments. Table 1 summarizes the LDL towards landfill classes of WT1 and EOS507F and the concentration ranges of the samples considered for the TS.

	WT1		**EOS507F**	
Odour class	**LDL (ou_E/m^3)**	**Odour concentration range (ou_E/m^3)**	**LDL (ou_E/m^3)**	**Odour concentration range (ou_E/m^3)**
Fresh Waste	80	80 – 8000	30	30 – 260
Landfill Gas	70	70 – 5800	20	20 – 350
Lecheate	80	80 – 600	50	50 - 430

Table 1. Lower Detection Limit (LDL) and odour concentration range of the TS of the two instruments involved

The WT1 LDL turned out to be about 80 ou_E/m^3. Therefore, the WT1 is suitable for monitoring landfill odour emissions at the fenceline, where odour concentrations lower than 100 ou_E/m^3 are hardly found. Conversely, the EOS507F LDL turned out to be lower than 30 ou_E/m^3. Thus, it can be effectively installed at the receptor, located at about 2 km South the landfill, where low odour concentrations are expected. Also non-odorous ambient air samples collected at the monitoring sites were analysed to define the "Air" class [4]. Data relevant to training samples were processed by PCA to explore the structure of the dataset, and obtain a graphic visualization of the e-noses discrimination capability between the different landfill classes. Further, classification models to be used for the classification of odours detected at the monitoring sites were built: a k-NN and SW linear algorithms were used respectively for the WT1 and EOS507F datasets. For the WT1, also a quantification model was built. Differing from the most common approach implemented in commercial e-noses, the proposed model consists of two steps, involving first the classification of detected odours and, then, the estimation of odour concentration based on the Partial Least Squares regression (PLS) model built for the class to which the odour has been attributed. Thus, the quantification model consists of four PLS - one for each landfill odour class - which were implemented considering the responses of both MOS and specific H_2S and NH_3 sensors to landfill odour samples at increasing concentrations.

2.4.Field performance testing

After the installation of the e-noses at the monitoring sites, performance tests were carried out in the field to verify the e-noses capability to detect and classify odours from the landfill under investigation. New samples independent from the TS were sampled at the emissions sources, and analysed by dynamic olfactometry [4]. The odour concentration measured by dynamic olfactometry were used to determine the dilution factors needed to obtain samples at different concentration levels, within the concentration range considered for the training. Then, the samples were presented to the e-noses by alternating diluted odour samples at different concentrations to odourless ambient air samples, in order to simulate the odour events that might occur at receptors or plant fenceline. The range of the odour concentrations of samples used for performance testing are reported in Table 2.

	Odour concentration range of field test samples (ou_E/m^3)	
Odour class	**WT1**	**EOS507F**
Landfill gas	43 - 2900	25 -165
Fresh waste	20 - 4000	27 - 164
Leachate	51 - 600	25 - 175

Table 2. Odour concentration ranges of the odour samples used for field performance testing

The analysis of landfill samples in the field allowed to verify the LDL determined during the training phase, and assess the instruments capability to detect and classify landfill odours. The detection and classification performances were expressed in terms of accuracy indexes, respectively $AI_{detection}$ and $AI_{classification}$ [4]. Moreover, field performance testing involved the assessment of the IOMS Lower Classification Limit (LCL), representing the lowest odour concentration at which the IOMS is capable of correctly classifying the odour sample [4]. Performance testing involved also the verification of the WT1 capability to provide a reliable estimation of the odour concentration at the landfill fenceline. This verification was carried out by comparing the odour concentrations of field samples estimated by the IOMS with the real concentration determined by dynamic olfactometry. In this phase, the novel quantification model proposed in this paper was compared with a quantification model built neglecting sample classification, with the purpose to investigate the effect of the inclusion of a classification step prior to quantification on the precision of the model.

Odour impact assessment

The assessment of the odour impact of an industrial activity requires the estimation of the odour exposure at the receptor. In the case of IOMS monitoring, the odour impact is expressed as the frequency with which the IOMS, installed at the receptor, detects the presence of odours attributable to the plant under investigation. The acceptability of the odour impact assessed by the IOMS can be evaluated referring to the German guideline "GIRL—Geruchsimmision-Richtlinie" dated 13 May 1998 [16]. All data recorded during the monitoring period were processed by classification models built on the training samples, in order to provide a qualitative characterization of e-noses detections at the monitoring sites. The EOS507F detections, used to directly estimate the landfill odour impact at the receptor, were validated by evaluating them in combination with wind speed and direction relevant to the monitoring period. Indeed, the EOS507F detections of landfill odours occurring when the wind had an incompatible direction with the location of the receptor were considered as false positives, and excluded. As further validation step, the EOS507F detections were compared with the WT1 responses. When the EOS507F registered the presence of odours from the landfill at the receptor, then also the WT1 was expected to register the presence of odour at the plant fenceline [8]. After validation, the frequency over the monitoring period with which the EOS507F attributed the analysed air to landfill odour sources was assessed.

3. Results

Field performance testing

The results of the field tests carried out at the plant fenceline confirmed the LDL determined in the training phase. The WT1 proved to be capable to detect and correctly classify landfill samples having an odour concentration above the LDL (Table 1). Thus, the LCL towards landfill odour sources coincides with the LDL. Concerning the classification performance, the WT1 proved to be capable to detect landfill odours with an $AI_{detection}$ of 96%, and to distinguish the different landfill classes with an $AI_{classification}$ of 92%. Referring to the limit value of 70% established by the VDI 3518-3:2018, the achieved $AI_{classification}$ proved a good performance of the WT1 in terms of classification accuracy. Furthermore, field tests at fenceline focused on the verification of the WT1 odour quantification performance, with the purpose of evaluating the possibility to use the IOMS as fast and cheap tool for the continuous assessment of the odour concentration in ambient air. Therefore, the odour concentration of field tests samples determined by dynamic olfactometry was compared with the WT1 estimation based on the quantification model "A", developed in the training phase (Figure 1).

Figure 1 highlights that, for almost all landfill samples presented to the instrument for quantification performance testing, the odour concentration estimated by the WT1 is within the confidence interval of the olfactometric measurement. Only for two landfill gas samples, which were misclassified as "Fresh Waste" samples, the estimated odour concentrations fall out of the confidence interval relevant to dynamic olfactometry. These satisfactory quantification results highlight the need of using sample classification as input for the construction of effective quantification models. Indeed, the analysis of samples, having the same odour concentration, but collected at diverse sources, may result in very different e-nose odour fingerprints and signal amplitudes. For the purpose of verifying this aspect, field tests were processed also by a second quantification model ("B"), involving only one PLS regression, without considering sample classification prior to quantification. In general, model B overestimated the odour concentration, especially in the case of fresh waste samples (Figure 2). Moreover, all the estimated concentrations are very close to the median concentration of samples involved, i.e. about 1000 ou_E/m^3. This proves that quantification models built without first considering the sample class are imprecise, and cannot be used for an effective real-time monitoring of odour concentration at the fenceline.

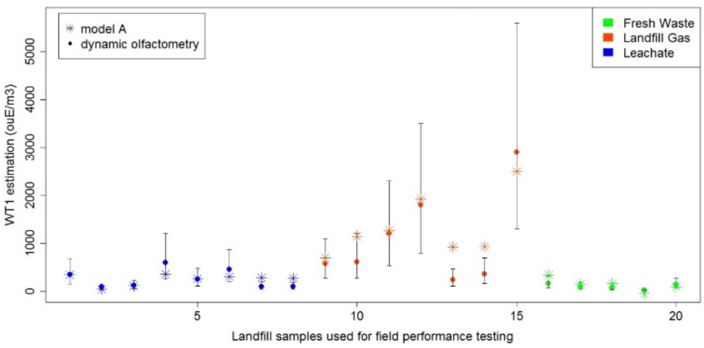

Figure 1. Comparison of the odour concentration by quantification model A and dynamic olfactometry

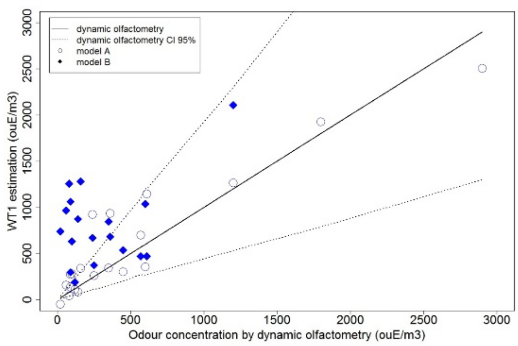

Figure 2. Comparison of quantification models A and B

Field tests confirmed also the EOS507F LDL towards landfill odours determined during the training phase, proving the instrument capability to correctly classify landfill samples having an odour concentration very close to the LDL (Table 1). Concerning the EOS507F classification performance, $AI_{detection}$ and $AI_{classification}$ of respectively 95% and 91% were determined. Given the very low concentrations of the samples, representative of typical of receptor conditions, these results are indicative of a very good performance of the Sacmi EOS507F in terms of classification accuracies, thus proving it as an effective tool for monitoring odour emissions from landfills.

Monitoring results & Odour impact assessment

As already mentioned, the landfill odour impact at a receptor can be directly assessed by one IOMS installed where the odour presence is lamented, in terms of the frequency of odour detections attributable to the plant under investigation over the monitoring period. However, the present case study proposes the adoption of two e-noses, differing in hardware and performances, to be installed at receptor and landfill fenceline, respectively. The aim of this approach was to combine the classification provided by the EOS507F at the receptor during the monitoring with the information collected by the WT1 at the fenceline. In particular, besides validating IOMS detections at the receptor and provide a reliable assessment of the odour impact, the study investigated the possibility to involve IOMS at plant fenceline to operate a real-time process monitoring. Given the higher concentration levels and the lower probability to deal with interferring odour sources at the plant fenceline than at receptors, an IOMS monitoring at the plant fenceline should theoretically be "easier" than at receptor. Thus, an IOMS installed at the plant fenceline should be able to provide a more precise estimation of the odour concentration, which could be used to set "warning" thresholds in order to promptly identify plant malfunctions that might result in odour events at the receptor. In this case, the EOS507F detected odours attributable to landfill gas and fresh waste odours for 2.6% and 2.7% of the monitoring, respectively. For 1.3% of the monitoring period the e-nose detected odours that were classified as "unknown". Those "unknown" detections occurred under favourable weather conditions (i.e. wind blew from north to south) were not excluded, since the classification of an odour as "unknown" does not necessarily exclude the possibility that it comes from the landfill, but just that it does not belong to any of the odour classes considered during the training. In conclusion, the odour impact at the receptor resulted in 6.6%, which can be considered acceptable according to the GIRL. With the purpose of evaluating the possibility to identify specific thresholds for the odour concentrations at fenceline that might result in odour events at the receptor, the odour events at the receptor attributed to the landfill were investigated in combination with the information (classification and concentration) provided by the WT1 installed at fenceline (Figure 3).

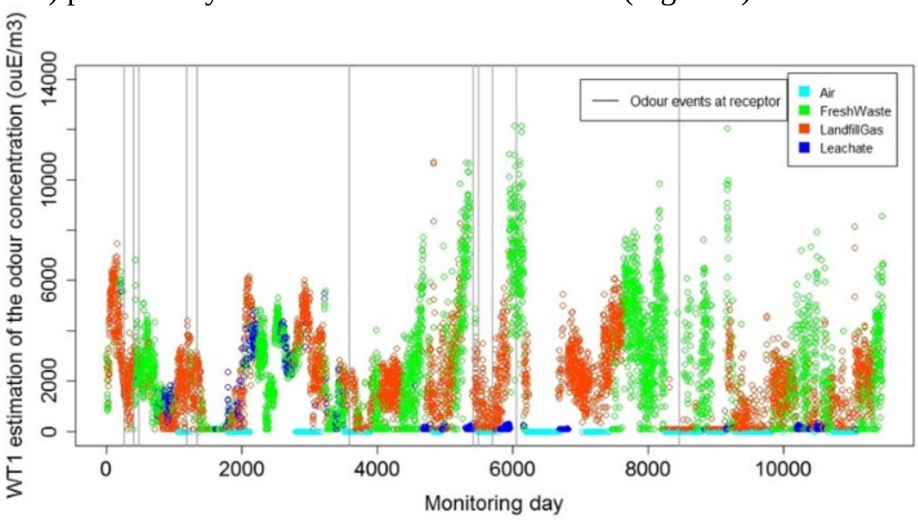

Figure 3. Odour concentrations estimated at the fenceline during the monitoring period

The comparison highlighted the existence of a correlation among the detections of high odour concentrations at the fenceline and the occurrence of odour episodes attributable to the landfill at the receptor. In particular, everytime an odour event attributable to the landfill was registered at the receptor, the odour concentration at the fenceline was above 1000 ou_E/m^3. Detections of "unknown" odours at the receptor occurred when the WT1 detected the presence of odours attributable to more than one landfill source (i.e., oscillation among “Fresh waste” and “Landfill gas” odours) and the odour concentration at the fenceline was lower than 700 ou_E/m^3. In that cases, probably the odours reaching the receptor were mixed and hardly distinguishable, giving that the EOS507F was not capable to attribute them to any of the landfill sources considered during training. These results proved the possibility to use the measurement of odour concentration at the fenceline to operate a continuous process control. However, there were several situations in which the odour concentration at the fenceline was above 1000 ou_E/m^3, without resulting in the detection of odours at the receptor. Thus, the investigation carried out within this study also highlights the need to combine to information provided by the IOMS at the fenceline with the specific meteorological conditions, and especially wind direction and atmospheric stability class, in order to improve the correlation between odour concentration measurements at the plant fenceline and the probability of occurrence of odour events at receptor.

4. Conclusion and future outlook

This paper presents the odour monitoring of a landfill performed by two different IOMS installed at a receptor and at landfill fenceline, respectively. The results obtained prove the possibility to use IOMS not only for providing a qualitative characterization of ambient air at monitoring sites, but also an accurate real-time estimation of the odour concentration at the landfill fenceline. This real-time estimation could be used to identify “warning” concentration thresholds, which should be based on the consideration of the specific meteorological conditions of the monitoring site.

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