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Review

# Measuring odours in the environment vs. dispersion modelling: A review

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## HIGHLIGHTS

- Techniques for measuring odours in the field are reviewed.
- The possibility of relating results of field odour measurements and model outputs is investigated.
- Chemical analysis, though reliable and consolidated, is mostly unsuitable for odour assessment.
- Human panels (trained or untrained) are necessary for direct assessment of odour in the field.
- Electronic noses or sensors represent a promising technology for environmental odour monitoring.

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## ABSTRACT

Source characterization alone is not sufficient to account for the effective impact of odours on citizens, which would require to quantify odours directly at receptors. However, despite a certain simplicity of odour measurement at the emission source, odour measurement in the field is a quite more complicated task. This is one of the main reasons for the spreading of odour impact assessment approaches based on odour dispersion modelling. Currently, just a very limited number of reports discussing the use of tracer gas dispersion experiments both in the field and in wind tunnels for model validation purposes can be found in literature. However, when dealing with odour emissions, it is not always possible to identify a limited number of tracer compounds, nor to relate analytical concentrations to odour properties, thus giving that considering single odorous compounds might be insufficient to account for effective odour perception. For these reasons, the possibility of measuring of odours in the field, both as a way for directly assessing odour annoyance or for verifying that modelled odour concentrations correspond to the effective odour perception by humans, is still an important objective. The present work has the aim to review the techniques that can be adopted for measuring odours in the field, particularly discussing how such techniques can be used in alternative or in combination with odour dispersion models for odour impact assessment purposes, and how the results of field odour measurements and model outputs can be related and compared to each other.



## 1. Introduction

Since several decades, it is known that the odours resulting directly or indirectly from human activities may cause adverse effects on citizens (Aatamila et al., 2011; Sucker et al., 2009; Witherspoon et al., 2004), and are recently being considered as atmospheric contaminants. It is important to highlight that odours are, among atmospheric pollutants, the major cause of population's complaints to local authorities (Henshaw et al., 2006). Indeed, several conventional pollutants are generally not perceived by population, even if they might be harmful for human health, especially if normal exposure limit concentrations are exceeded. On the contrary, some odours are perceived far below normal exposure limit concentrations, due to the presence of odorous compounds having extremely low odour detection threshold concentration (Nicell, 2003).

For these reasons, odours are nowadays subject to control and regulation in many countries (Nicell, 2009). The need to regulate

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odour impacts entails the requirement of specific methods for odour measurement.

Dynamic olfactometry (CEN, 2003) is now a widespread and common technique for the quantification of odour emissions in terms of odour concentration (Muñoz et al., 2010). Unfortunately, source characterization alone is not sufficient to account for the effective impact of odours on citizens. For the purpose of evaluating citizens' exposure to odours it would be useful to quantify odours directly at receptors. However, despite a certain simplicity of odour measurement at the emission source, odour measurement in the field is a quite more complicated task (Brandt et al., 2011a; Gostelow et al., 2001).

These difficulties are among the reasons for the spreading of odour impact assessment approaches based on odour dispersion modelling. Odour dispersion models allow to simulate how odour disperses into the atmosphere, and therefore to calculate ground odour concentration values in the simulation space-time domain (Capelli et al., 2011a; Sheridan et al., 2004; Sarkar et al., 2003a; Schauberger et al., 1999), thereby entailing the advantage of being not solely descriptive (as field measurements), but also predictive. Actually, nowadays, most odour regulations all over the world are defined based on the application of dispersion modelling.

In some cases, odour regulations fix acceptability standards in terms of the frequency with which a given odour concentration is exceeded (JORF, 2008; Regione Lombardia, 2012). One example of this approach is the "Integrated Pollution Prevention and Control (IPPC) – Horizontal Guidance for Odour Part 1 – Regulation and Permitting" published by the Environmental Agency of the United Kingdom (UK Environmental Agency, 2002). The approach it takes is to establish exposure criteria in terms of ground level odour concentration at the 98th percentile, i.e. the maximum odour concentration that may only be exceeded for 2% of the hours in a year. The limits set by the guidelines are expressed in terms of hourly average odour concentration values at the 98th percentile, and are differentiated on the basis of the level of potential olfactory annoyance ("low", "medium" or "high") associated with the industrial category under consideration (Table 1).

In other cases, odour regulations specify the minimum distance from the closest inhabited area where possible odour-producing industrial or agricultural facilities can be located. Historically, minimum distances were tabulated, by taking into account the use (e.g., residential or agricultural area) or the residential density of the area in which the facility is located (Melse et al., 2009; JORF, 2005; Piringer and Schauberger, 1999; VROM, 1996). More recently, minimum distances are not tabulated but calculated by directly applying dispersion models (Piringer et al., 2007; Schauberger et al., 2002) or by using simplified mathematical expressions containing specific coefficients derived from dispersion modelling (Schauberger et al., 2012).

In general, different types of models can be used to simulate the dispersion of pollutants into the atmosphere (Mazzoldi et al., 2008; Holmes and Morawska, 2006; Caputo et al., 2003). Independently from the model used, model validation is fundamental in order to evaluate model reliability. Currently, reports on studies for validation of odour dispersion models are limited in literature (Hayes et al., 2006), even though some studies discussing the use of tracer gas dispersion experiments both in the field and in wind tunnels for model validation purposes can be found in literature (Abdul-Wahab et al., 2011; Dresser and Huizer, 2011; Latos et al., 2011; O'Shaughnessy and Altmaier, 2011; Santos et al., 2005; Vieira de Melo et al., 2012).

**Table 1**
Exposure criteria in terms of ground level odour concentration as a 98th percentile, in the United Kingdom.

| Relative "offensiveness" of odour | Indicative criterion |
|---|---|
| HIGH (e.g., activities involving putrescible waste, processes involving animal or fish remains, wastewater treatment, oil refining) | 1.5 $ou_E$ $m^{-3}$ 98th percentile |
| MEDIUM (e.g., intensive livestock rearing, fat frying, sugar beet processing) | 3.0 $ou_E$ $m^{-3}$ 98th percentile |
| LOW (e.g., chocolate manufacture, brewery, fragrance and flavourings, coffee roasting, bakery) | 6.0 $ou_E$ $m^{-3}$ 98th percentile |

In the case of odour dispersion simulation, especially in the case of complex sources, it is not always possible to identify a limited number of tracer compounds (Capelli et al., 2012a). Moreover, given the difficulty of relating analytical concentrations to odour properties, considering single odorous compounds might be insufficient to account for effective odour perception (Dincer et al., 2006; Dincer and Muezzinoglu, 2007; Sarkar and Hobbs, 2002).

For these reasons, the possibility of measuring odours in the field, both as a way for directly assessing odour annoyance or for verifying that modelled odour concentrations correspond to the effective odour perception by humans, is still an important objective.

Different approaches and techniques can be used for measuring odours in the environment.

Such techniques include physical and chemical measurements for either the quantification of the concentration of one sole compound or the evaluation of global pollution (i.e. concentration of odorous compounds and VOCs), by means of exhaustive chemical analysis (Saral et al., 2009; Kim and Park, 2008) or, recently, electronic noses (Romain et al., 2008; Littarru, 2007; Stuetz et al., 1999).

Other techniques are based on sensorial measurements, such as dynamic olfactometry. As already mentioned, dynamic olfactometry should in general be limited to source sampling, however, it has in some cases been applied for ambient air sampling and analysis (Capelli et al., 2008a).

As an alternative, instead collecting samples on field and then analysing them in laboratory, it is possible to use human "sensors" directly in the field (Nicell, 2009).

Human "sensors" may be the resident population, who may collect records of odour episodes over prolonged periods of time to be compared with model results (Sironi et al., 2010; Drew et al., 2007; Sarkar et al., 2003b).

Otherwise, it is possible to rely on trained assessors, for instance by using a field olfactometer to determine the presence and intensity of odour directly on field (Nicell, 2009; Schiffman et al., 2005), or by running field inspections such as grid or plume measurements to evaluate the extent of the area impacted (Guillot et al. 2012; Mussio et al., 2001; Nicolas et al., 2006).

This paper has the object of reviewing the techniques that can be adopted for measuring odours in the field (i.e., at receptors), with the particular aim of discussing how such techniques can be used as an alternative or in combination with odour dispersion models for odour impact assessment purposes, and how the results of field odour measurements and model outputs can be related and compared to each other.

## 2. Development and application of odour dispersion models

### 2.1. Models for pollutant dispersion simulation

In general, different types of models can be used to simulate the dispersion of pollutants into the atmosphere (Mazzoldi et al., 2008; Holmes and Morawska, 2006; Caputo et al., 2003).

The simplest models are analytical stationary plume models. Among them, Gaussian models, for which turbulent dispersion is parameterized with empirical coefficients derived from experimental campaigns, are the most traditional ones and very cheap for computation (Gifford, 1959; Pasquill, 1961; Smith, 1995). Critical conditions for the use of such models are low winds (calm conditions) and complex terrain (Luhar, 2011; Thomson and Manning, 2001). More advanced models are hybrid models, for which dispersion is parameterized directly from meteorological data giving information about the thermal and mechanical structure of the lower atmospheric layers (Ganguly and Broderick, 2010).

Puff models (Cao et al., 2011; Lamb and Neiburger, 1971) are improved from Gaussian plume models to be applied to non-stationary and non-homogeneous flow by representing a plume by a series of independent elements (puffs) that evolve in time as a function of temporally and spatially varying meteorological conditions (Jung et al., 2003). Puff models applied to odour dispersion are able to simulate the instantaneous characteristics of odour perception (De Melo Lisboa et al., 2006). First applications of puff models for odour dispersion are linked to studies of Högström (1972).

Lagrangian particle models and Eulerian grid models (3-D models) are more advanced tools for atmospheric dispersion simulation. The first simulate the dispersion of the emitted pollutants with computational particles moving in the wind field and three-dimensional turbulence field. The latter numerically solve the diffusion equations of the pollutant emitted in the three-dimensional domain subdivided in grids of variable dimensions (Nguyen et al., 1997). Their limits consist in the incomplete knowledge of the turbulence mechanisms and the very high computational time required for complex simulations (Lagzi et al., 2004; Franzese, 2003; Raza et al., 2002; Wilson and Sawford, 1996).

Most complex models are fluid dynamic models (i.e., CFD: Computational Fluid Dynamics), which solve three-dimensional equations for wind, temperature, humidity and concentrations (Pontiggia et al., 2009). Such models are used for extremely time and spatially detailed simulations, considering the presence of obstacles or buildings explicitly in the model, and are currently applied also to odour dispersion modelling (Maïzi et al., 2010; Lin et al., 2007).

In general, all the above mentioned model typologies, in some cases with opportune precautions, may be successfully applied to the simulation of odour dispersion.

This work hasn't the aim of comparing or discussing in detail the characteristics of different models.

The choice of the most adequate model for a given application should be evaluated case by case based on several factors (Turner, 1979). Steady-state models (i.e. simple or advanced Gaussian plume models) can successfully be applied when the requested outcome is the worst-case condition. More sophisticated models include more complex parameterizations. They also require more meteorological input, more computer time and more expertise. Whether it is worth to spend extra efforts to gather both data and expertise depends on the type of application, the locations of the sources and receptors, source types, complexity and variability of the meteorology, desired accuracy of the results and averaging time (Escoffier et al., 2010).

In general, the models that are most commonly used for odour dispersion modelling purposes are Gaussian models (e.g., AERMOD) and CALPUFF. Recent studies tend to prefer CALPUFF, due to the limitations of Gaussian models, including the inability to handle calm and stagnation conditions, lack of three-dimensional meteorology and steady-state assumption (Barclay and Borissova, 2013). Moreover, other studies prove AERMOD to significantly overestimate concentrations, especially during stable atmospheric conditions (Dresser and Huizer, 2011; Busini et al., 2012).

### 2.2. Model inputs

In general, for the application of an atmospheric dispersion model, at least three different kinds of input data are needed: meteorological, topographical, and emission data (Capelli et al., 2011b; Sattler and Devanathan, 2007).

This section discusses the quality requirements for the above mentioned model input data.

#### 2.2.1. Meteorological data

The acquisition and pre-processing of meteorological data is of crucial importance for atmospheric dispersion modelling purposes (Davakis et al., 2007; Brandt et al., 1998).

In general, the meteorological data required for dispersion modelling include wind speed, wind direction, and information about the atmospheric stability conditions (i.e. mixing height and turbulence), which can be derived from other meteorological parameters, such as humidity, temperature and wind speed profiles, as well as cloud covering or solar radiation (global or net), depending on the meteorological pre-processor used (Mandurino and Vestrucci, 2009).

Of course, the detail and the quality of the input requirements depend on the sophistication of the model used.

Older dispersion models, i.e. simple Gaussian plume models, are based on the use of the Pasquill-Gifford-Turner stability classes for the characterization of the vertical and lateral dispersion (EPA, 1995). Instead, the new generation of short-range dispersion models, including more complex Gaussian plume models such as ISC3, AERMOD and ADMS, use Monin-Obukhov similarity to describe the mean and turbulence structure in the surface boundary layer. The ground-level concentration is generally expressed in terms of specific variables, such as the surface friction velocity and the Monin-Obukhov length, which contain information on the turbulence and the mean wind that govern dispersion (Vankatram, 2004).

More sophisticated, non-steady-state models, i.e. Lagrangian puff (e.g., CALPUFF; SCIPUFF) or particle (e.g., NAME, AUSTAL) models, Eulerian models (e.g., CMAQ, CALGRID) and hybrid models (e.g., HYSPLIT), have the common characteristics that they can input a three-dimensional dataset of meteorological information. As for the advanced Gaussian models, these models compute dispersion coefficients internally with various refined parameterizations using imported or evaluated micro-meteorological parameters (Caputo et al., 2003; Escoffier et al., 2010).

In principle, meteorological data can be obtained from one single meteorological station. If the data required cannot be obtained from one station (for instance because of high quantity of vacancies or invalid data), available data should possibly be integrated with those registered by another station, thereby evaluating the compatibility between the two stations, as to avoid that the combination of different data may compromise their representativeness.

An important aspect to be considered when choosing the meteorological station is its distance from the emission source: in cases of complex terrain, the meteorological station shall be located in the same valley or in a position as to be representative of the wind conditions of the considered emission. This is particularly true for the wind speed and wind direction data.

The data registration frequency and the extension of the simulation time domain may depend on the simulation purposes. In general, for odour impact assessment and comparison with acceptability criteria such as the frequency of exceeding of a given odour concentration, as provided by most odour regulations worldwide (Mahin, 2001), data should be recorded for at least one complete year, with a hourly frequency, or higher (e.g., every 15 min).

If sufficient meteorological data are not available from nearby stations, supplementary meteorological surveys may be conducted using a mobile station installed at the site under investigation. The duration of these surveys may be shorter than the entire simulation domain, but it should be sufficient as to make it possible to extrapolate the trend of the meteorological parameters for the whole time domain.

### 2.2.2. Topographical data

The spatial domain of the simulation should be chosen as to include all the emission sources to be studied, as well as the receptors that are believed to be impacted by the emitted odours, and their geographical coordinates, i.e. latitude and longitude, either in the UTM-WGS84 (Universal Transverse of Mercator – Word Geodetic System 1984) or UTM-Gauss-Bouga System, shall be indicated.

If the orography of the terrain included in the spatial domain is complex, its effects shall be taken into account in the simulations, by adopting suitable algorithms and setting the elevations of each receptor point of the simulation grid.

Most dispersion models include the possibility of considering the effect of the presence of buildings, called "building downwash", by setting the building position and height as model inputs (Canepa, 2004).

### 2.2.3. Emission data

As for the simulation of dispersion of any pollutant, also in the case of the dispersion of odours, it is not sufficient to consider the pollutant (odour) concentration, but it is necessary to account for the air flow associated with the monitored odour source. In the case of odour, the parameter to be considered for dispersion modelling purposes is the Odour Emission Rate (OER), which is expressed in odour units per second ($ou_E\ s^{-1}$), and is obtained as the product of the odour concentration and the air flow associated with the source. The volumetric air flow shall be evaluated in normal conditions for olfactometry: 20 °C and 101.3 kPa on wet basis (CEN, 2003).

The method for the estimation of the OER from an odour source depends on the source typology. For this reason, different sampling strategies should be adopted in function of the source to be monitored (Bockreis and Steinberg, 2005).

In the case of point sources, where odour is emitted from a single point, generally in a controlled manner through a stack, sampling consists in the withdrawal of a fraction of the conveyed air flow. The emitted air flow can be calculated by measuring the air velocity and the duct transversal section, and then the OER is obtained as follows:

$$\mathrm{OER} = Q_{\mathrm{air}} \cdot c_{\mathrm{od}}$$

OER = Odour Emission Rate ($ou_E\ s^{-1}$)
$Q_{\mathrm{airl}}$ = effluent volumetric air flow ($m^3\ s^{-1}$)
$c_{od}$ = measured odour concentration ($ou_E\ m^{-3}$)

In the case of area sources, where emissions typically come from extended solid or liquid surfaces, it is first necessary to distinguish between: active sources, which have an outcoming air flow (e.g., biofilters or aerated heaps), and passive sources, where there is no outcoming air flow and the mass flow from the surface to the air (volatilization) is due to phenomena such as equilibrium or convection (e.g., landfill surfaces and wastewater treatment tanks).

As a limit for the distinction between the above mentioned kinds of sources, the German guideline VDI 3880 (2011) fixes a specific flux of 50 $m^3\ h^{-1}\ m^{-2}$: sources having a volumetric outcoming air flow above this value are to be considered as active sources, otherwise they are considered as passive.

In the case of active area sources, because sampling is performed by means of a "static" hood that isolates a part of the emitting surface, channelling the outward air flow into the hood outlet duct, and therefore realizing the same modality used for point sources, the OER can be estimated applying the same expression used for point sources.

In the case of passive area sources, the estimation of the OER is a rather complicated process, as it is difficult to measure a representative odour concentration, and, most of all, to determine a well-defined air flow rate.

In general, the estimation of emission rate values from passive area sources may be performed by adopting two different approaches (Hudson and Ayoko, 2008a): either indirect measurements, using micrometeorological methods, where emission rates are derived from simultaneous measurements of wind velocities and concentrations across the plume profile downwind the source; or direct measurements, using an enclosure of some sort, i.e. so called "hood methods", whereby emission rates are derived from the data regarding the concentration of the compounds of interest measured in the samples collected at the outlet of the sampling device combined with the dimensions of the device and the operating conditions.

In general, indirect techniques require a large number of samples to characterize the considered emission, thus making such techniques impractical for odour assessments. For this reason, hood methods are by far the techniques that are most widely used for the evaluation of emission rates from passive area sources.

As far as direct measurements are concerned, various sampling devices have been designed and tested for sample collection from a range of area sources (Capelli et al., 2009; Hudson and Ayoko, 2008b; Frechen et al., 2004). In spite of the differences, all these devices are based on the same principle: to isolate a portion of the emitting surface by means of a hood, to insufflate a neutral (i.e. odourless) air stream and finally to measure the odour concentration at the hood outlet.

The estimation of the OER requires the calculation of another significant parameter, i.e. the Specific Odour Emission Rate (SOER), expressed in odour units emitted per surface and time unit ($ou_E\ m^{-2}\ s^{-1}$), according to the following equation:

$$\mathrm{SOER} = \frac{Q_{\mathrm{air}} \cdot c_{\mathrm{od}}}{A_{\mathrm{base}}}$$

SOER = Specific odour Emission Rate ($ou_E\ m^{-2}\ s^{-1}$)
$Q_{air}$ = air flow rate inside the hood ($m^3\ s^{-1}$)
$c_{\mathrm{od}}$ = measured odour concentration ($ou_E\ m^{-3}$)
$A_{base}$ = base area of the hood ($m^2$).

The OER is then calculated by multiplying the SOER by the emitting surface of the considered source:

$$\mathrm{OER} = \mathrm{SOER} \cdot A_{\mathrm{em}}$$

OER = Odour Emission Rate ($ou_E\ s^{-1}$)
SOER = Specific odour Emission Rate ($ou_E\ m^{-2}\ s^{-1}$)
$A_{\mathrm{em}}$ = emitting surface of the considered source ($m^2$).

When dealing with passive area sources, an important aspect to be considered for dispersion modelling purposes is that, given that the functioning principle of such hoods, also called "wind tunnels", is to realize a mass transfer to a gas phase due to forced convection, thus simulating the wind action on the monitored surface, the OER is a function of the air flow above the surface.

By applying the Prandtl boundary layer theory (Thibodeaux and Scott, 1985) for the description of the phenomenon, it is possible to demonstrate that both the SOER and the OER are proportional to the square root of the air velocity (wind speed) above the monitored surface (Sohn et al., 2005; Bliss et al., 1995):

$$\text{SOER, OER} \propto v^{1/2}.$$

For this reason, dispersion models should account for this dependence and thus re-calculate the OER for each hour of the simulation domain according to the actual wind speed.

Other odour sources that might be considered for dispersion modelling are diffuse volume sources, which are typically buildings from which odours come out, intentionally, through naturally ventilated ducts, as well as unintentionally, through doors, windows or other openings. It is not always possible to correctly characterize the emissions from such sources, as it is difficult to measure a representative odour concentration and, often, it is not possible to define a precise air flow. For this reason, the OER estimation of such sources is, in general, very complicated, thus requiring suitable hypotheses and techniques for the evaluation of the emitted odour (Bokowa and Liu, 2008).

Besides the OER relevant to any source (point, area, or diffuse), further data are required as model inputs.

First the geographical location of the sources should be identified precisely in the simulation spatial domain. Moreover, the geometry of the source should be identified, e.g., height, diameter (or equivalent diameter if the outlet section is not circular), orientation (vertical, inclined or horizontal). Finally, the physical data of the emission, e.g., air flow/speed and temperature, have to be specified, as well.

In general, the uncertainty associated with dispersion modelling depends on the uncertainty of the adopted model, but also on the uncertainty associated with the model input data (Dabberdt and Miller, 2000; Colvile et al., 2002). In the specific case of odour dispersion modelling, the major contribution to the overall uncertainty is given by the emission data, due to the high uncertainty associated with the olfactometric analysis, which typically is one of the main drawbacks of sensorial techniques. Measurement uncertainty may vary significantly between different laboratories, and it is generally much lower for laboratories working according to the European Standard for dynamic olfactometry (CEN, 2003; Van Harreveld et al., 2009; Jonassen et al., 2012). Even though the topic of uncertainty relevant to olfactometric measurements is still very debated among the scientific community, there are some studies proving that the uncertainty of dynamic olfactometry can reach up to ±6 $dB_{od}$, which means an error band between one fourth and the fourfold of an actual measurement value (Maxeiner and Mannebeck, 2004; Boeker and Haas, 2007, 2008; Van Boheemen, 2012).

### *2.3. Validation of odour dispersion models*

As already mentioned, dispersion models can be more or less complex. Independently from model complexity, model validation is an important aspect that cannot be set aside. Indeed, “strict” validation studies are limited in literature (Hayes et al., 2006). One difficulty is that chemical analyses, which are easily carried out at the source or close to the source (see par. 3), are hardly applicable for model validation due to the low, or even very low, level of pollutants, which is often below the analytical detection threshold. Limitations are due also to the fact that the provenance of the detected compounds is not always unequivocally identifiable. For this reason, dispersion modelling based on chemical measurements at the source and in the environment should be focused on the identification of specific “tracer” compounds. In some cases, it is possible to identify a limited number of compounds that can be linked to the source, such as hydrogen sulphide (Latos et al., 2011; O’Shaughnessy and Altmaier, 2011), sulphur dioxide (Dresser and Huizer, 2011) or ammonia (Blanes-Vidal et al., 2012). Another solution is to introduce a new tracer. Sulphur hexafluoride ($SF_6$) is a compound that is typically used as a tracer for dispersion experiments (Connan et al., 2011; Van Dorpe et al., 2007). The advantages of using $SF_6$ as a tracer for dispersion modelling purposes are mainly three: first, the warranty of specificity due to the fact that this compound is not present in the environment, second, it is stable (non- reactive), at last, specific detection techniques (which are generally based on optical measurements) allow to reach very low detection levels (μg $m^{-3}$ level).

An example of model validation by means of $SF_6$ tracer experiment is given by Connan et al. (2011): their study shows that Briggs and ADMS models give acceptable results in neutral atmospheric conditions.

Radioactive tracers (natural or anthropogenic) have been also used for atmospheric dispersion studies (Sykora and Froehlich, 2010). Of course, validation studies with radioactive compounds or other hazardous chemicals need authorizations and must be carried out by experts used to manipulate such compounds.

If a tracer injection cannot be carried out on field, a small scale study can be developed into a wind tunnel. Of course, the scale factor with respect to odour cannot be easily estimated, but such studies are generally designed with the purpose of understanding diffusion and transportation of compounds around buildings or other obstacles. Typically, a small scale area representative of a real one can be constructed. In that case, dispersion at urban street canyons and intersections is studied (Ahmad et al., 2005). Moreover, wind tunnel study results can be compared with field observations as shown by Aubrun and Leitl (2004). In their study the authors demonstrate the ability to replicate the unsteady properties of a dispersion process inside a wind tunnel. Depending on the concept of the wind tunnel, different parameters can be controlled (e.g., air humidity and temperature), and heating devices can simulate solar radiation. Wind tunnel studies can also be linked with emission experiments whereby a wind tunnel is designed for simulating a source of odorous pollutants and to test emission models as a first step of the dispersion process (Santos et al., 2012).

## 3. Physical and chemical measurements

The presence of odours in the environment may be evaluated based on chemical measurements, which are easier to carry out compared to direct odour measurements, even though results are not typically comparable.

If some pollutants are responsible of the odour (and the annoyance), these compounds can be followed as tracers for odour activity and in that way, a dispersion model can be used with measured concentrations as inlet data. Of course, for modelling purposes, chemical measurements must be carried out including all data and physical measurements required for the model. In a classical way of dispersion, the source is characterized and measurements in the environment give data to estimate the precision of a model.

If the source cannot be characterized, the pollution is measured in the field and with reverse dispersion, the emission rate is estimated but in that case, no real validation can be proposed, because the calculated results cannot be compared with unknown emission data. An example of reverse dispersion measurement is described by Schauberger et al. (2011). In this study, seven compounds (two acetates: butyl acetate, ethyl acetate, BTX: benzene toluene, m/p-xylene, o-xylene and a-pynene), were identified as odorants compounds of a thermal waste recycling plant and measured over a period of 1.5 years in the prevailing wind direction leeward of the plant. Typically in such studies, organic compounds are trapped on cartridges packed with solid sorbents to have measurable concentrations and then analysed by gas chromatography techniques after thermal desorption of cartridges. Some sorbents can be used as "universal" trap such as Tenax but in fact, it globally does not trap compounds with small carbon chain (<6 carbons). A variety of sorbents are available depending on hydrophobic criterion, carbon chain length, etc. All selection is based on physical or chemical properties and no link can be established with odorous compounds. In order to cover the larger screening of compounds, tubes are packed with complementary sorbents. The commercially available sorbents that can be used for applications with odorous compounds have been listed by Muñoz et al. (2010).

The method based on compound trapping into a cartridge packed with a sorbent is well developed for volatile organic compounds and it is applicable for odorous organic compounds but the choice of the sorbent is crucial. A non-specific sorbent used in a field experimentation can trap a lot of compounds from both anthropogenic and biogenic sources (Ciccioli et al., 2003). In a large screening, one or two tracers can be selected but if the odorous compounds are well identified, a more specific sorbent can be used in cartridges. Recent reviews describe all sampling methodologies for organic trace analysis in the air (Woolfenden, 2010a; 2010b).

As already mentioned, the chemical identification of odorous compounds is not directly correlated to the determination of odour properties. For the purpose of obtaining significant information about odours based on the results of chemical analyses in the field, thus trying to relate the chemical composition of an odorous mixture to its odour concentration, it is important to account for the odour potential of the identified compounds (which depends on their odour detection threshold concentration) and to calculate the so called Odour Activity Value (OAV), which represents the sum of the concentrations of the odorous compounds weighted with their Odour Threshold (OT) (Kubícková and Grosch, 1998; Nuzzi et al., 2008):

$$\mathrm{OAV} = \sum_{i=1}^{n} \frac{C_i}{\mathrm{OT}_i}$$

OAV = Odour Activity Value ($\mathrm{ou_E\ m^{-3}}$)
$C_i$ = Concentration of compound $i$ ($\mathrm{mg\ m^{-3}}$)
OT = Odour Threshold of compound $i$ ($\mathrm{mg\ ou_E^{-1}}$)

Still, the odour concentration calculated based on the OAV entails strong imprecision. One reason for this imprecision might be the difficulty of finding reliable OT values, given that the values that can be found in literature for a single odorous compound often differ by several orders of magnitude (Capelli et al., 2008a). Moreover, if synergic effects of odorous compounds are present, such a calculation will underestimate the odour concentration of the odorous mixture.

A study by Capelli et al. (2012b) reports the attempt of correlating the odour concentration ($c_{od}$) measured in correspondence of several odour sources of a complex industrial area including a steel industry, different chemical industries for the production of polypropylene, its products and other activities mainly for the treatment of wastewaters and solid waste both with the total VOC concentration and with the OAV. Fig. 1 and Fig. 2 show the correlation between total VOC concentration ($c_{od}$) and odour concentration and the correlation between OAV and odour concentration, respectively. It is possible to observe that the OAVs are about two orders of magnitude lower than the corresponding measured odour concentration values. This difference may be due to the already mentioned difficulty of finding reliable OT values. Another important observation concerns the fact that the correlation between OAV and $c_{od}$ ($R^2 = 0.836$) effectively turned out to be significantly better than the correlation between total VOC concentration and the $c_{od}$ ($R^2 = 0.393$). This result proves that the OAV, being a sort of total concentration weighted by the odour thresholds of the single compounds contained in an odorous mixture, does account for the different relative contribution of each compound to the mixture total odour concentration, and therefore is able to better describe the odour properties of an odorous mixture than just the total VOC concentration, which, on the contrary, does in no way account for the odour properties of the mixture components.

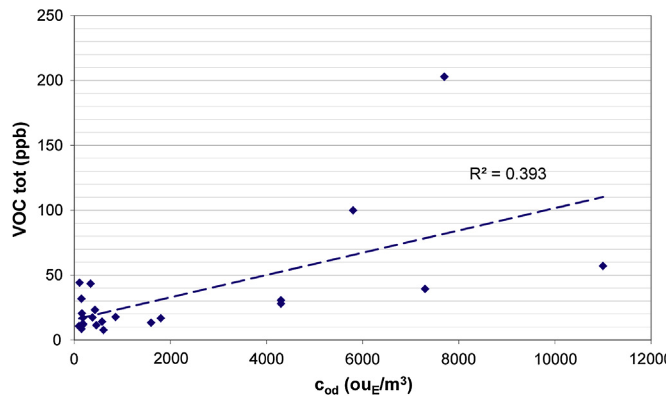


**Fig. 1.** Correlation between total VOC concentration and odour concentration.

## 4. Sensorial measurements

### 4.1. Olfactometric analyses: direct ambient odour measurement

Sensorial techniques allow the odour concentration to be quantitatively evaluated through dynamic olfactometry and the odour to be quantitatively assessed in terms of parameters such as hedonic tone (pleasantness or unpleasantness of the odour) quality (type of odour, described for instance based on a standard odour wheel) and intensity (perceived strength of odour sensation) (Suffet and Rosenfeld, 2007; Gostelow et al., 2001; Sneath, 2001). Odour concentration measurement by threshold dynamic olfactometry has become the most widely employed sensorial technique (Romain et al., 2008; Dincer and Muezzinoglu, 2007).

Dynamic olfactometry allows to measure the total effect of the odour on human perception (Gostelow and Parson, 2000) using the human nose as the detector, by quantifying the odour concentration of a sample as the number of dilutions with odourless air needed to reduce the odour concentration to its detection threshold. The analysis is carried out by presenting the diluted

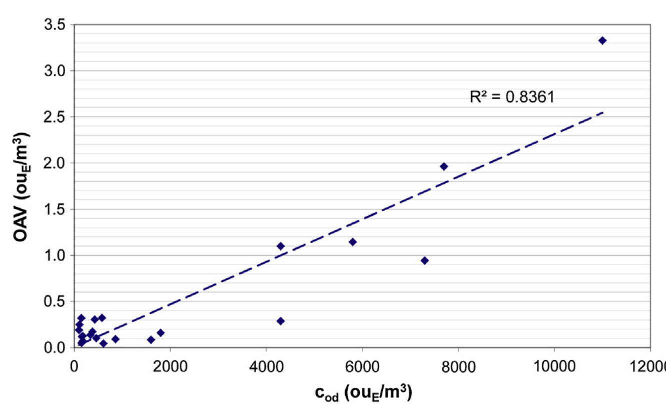


**Fig. 2.** Correlation between total OAV and odour concentration.

sample to a panel of selected and screened human assessors (4–10 panellists) using a dilution device called olfactometer (Capelli et al., 2010; Sneath, 2001). A selection of average-sensitivity panellists is recommended in order to produce more reproducible results while the gender of panellists does not bring any significant difference in olfactometry response (Van Harreveld et al., 2009; Bliss et al., 1996). Recent advances in the design and operation of olfactometers are gradually increasing their accuracy and precision, while lowering detection limit. Even with recent advances, the current detection limits are in the order of 20–50 $ou_E\ m^{-3}$, hence the applicability of olfactometry to assess ambient air samples around the threshold for nuisance levels (5–10 $ou_E\ m^{-3}$) is limited (Bokowa, 2012; Muñoz et al., 2010).

### 4.2. Comparison with neighbours' recordings

From a general point of view, the odour exposure is always a human feeling. For this reason, social participation may be very useful for odour exposure assessment purposes.

In one of their studies, Nicolas et al. (2010) defined three ways involving social participation:

- collecting and analysing complaints data;
- administering and analysing one-shot surveys concerning local residents;
- questioning resident panellists on repeated occasions or asking them to regularly complete odour diaries.

These three ways can give data about odour exposure but the different odour criteria between residents (intensity, duration or offensiveness) are not comparable and it could be difficult to evaluate which criteria was retained by residents. That is why the odour exposure defined in the European Standard (Guillot et al., 2012) is based on odour detection (Yes or No) to characterize an area on different points.

However, a methodology based on social participation may allow the origin of the odour episodes to be identified. A model of social participation that records data about frequency and duration of odour episodes can be useful in the process of odour episodes evaluation (Gallego et al., 2008).

Sensory databases can be built to measure the scale of annoyance, the effects detected and the potential sources of emissions, or questionnaires can be conducted in which odour emission can be correlated with hourly meteorological data (Nicolas et al., 2007). The database can be built using questionnaires (Stenlund et al., 2009; Roca et al., 2003; Aitken and Okun, 1992) that would include the date of the odour episode, the time the odour episode started and ended the location of odour, a description of both quality and intensity of odour. Data obtained from social participation are individually evaluated and associated with the meteorological parameters recorded during the episodes detected.

The perception of odour in the community is also fundamental to record odour incidents. Drew et al. (2007) examine perception of odour in the community in conjunction with the modelled odour dispersion. The results of this study show that with shorter averaging times, the modelled pattern of dispersion reflects the pattern of observed odour incidents recorded in a community monitoring database.

These kinds of study, using community modelling as a tool to find a link between dispersion and perception of odour, take almost one year during which people are engaged within the local community as regular odour monitors (Sarkar et al., 2003a,b).

The importance of involving the population and making them actively take part to an odour impact assessment study by means of questionnaires for reporting the odour episodes on the territory, as well as of using this information for comparison with the outcomes of the application of an odour dispersion model is described in a study by Sironi et al. (2010). In this case, the studied area comprised three small municipalities where four rendering plants are located near to each other. A 4-months questioning survey was conducted by collecting reports of perceived odour episodes in the three municipalities and then comparing them with the results of dispersion modelling, with the purpose of verifying if the odour plume simulated by the model effectively reached the receptors in correspondence of the odour episode reports. The comparison between odour perceptions and simulated ambient odour showed an average accuracy, expressed as the correspondence between odour perceptions and simulated odour immissions, of 86.5% (Table 2), therefore adding to the confirmation of the outcomes of the applied simulation procedure.

### 4.3. Field measurements with panellists

Field olfactometric surveys are seen as being more convenient for the determination of ambient air concentration close to the odour detection threshold as a result of their lower operating range, being comprised between 2 $ou_E\ m^{-3}$ and 500 $ou_E\ m^{-3}$ (McGinley and McGinley, 2004).

Different approaches can be used to estimate odour exposure or annoyance in a defined environment. Among all potential approaches, both grid and plume methods will be included in the next European Standard on odour exposure (Guillot et al., 2012). The differences between these methods are shortly described as follows: the grid method is a long period (one year) statistical survey method to obtain a representative map of a recognisable odour exposure over a selected area (Fig. 3), whereas the plume method is a short period method (several times of approximately half a day under different meteorological conditions) to determine the extent of recognisable odour from a specific source (Fig. 4). Both methods are based on odour detection and recognition by human panellists.

One interesting example of comparison between odour dispersion modelling by Calpuff and a grid field inspection is given in a study by Ranzato et al. (2012), in which the two techniques are applied to the assessment of the olfactory nuisance caused by an anaerobic treatment plant for municipal solid waste. An interesting result is that the two techniques assessed similar spatial extents of odour nuisance in terms of frequency of odour episodes. The dispersion modelling approach entails the advantage of being by far cheaper and applicable also for predictive purposes. However, fugitive sources are hardly modelled, because of uncertainties regarding timing, location and emission rates. On the other hand, field inspection accounts for the human perception of odours, but it is in general less precise than the model, especially if other interfering odours are present.

Of course, a field measurement can include more details for odour characterization. Sucker et al. (2008) describe a study where

**Table 2**
Correspondences between odour perceptions and simulated immissions.

| | | |
|---|---|---|
| Municipality no. 1 | Total no. of odour episodes | 49 |
| | No. of correspondences perceptions-model | 41 |
| | % of correspondences perceptions-model | 83.7% |
| Municipality no. 2 | Total no. of odour episodes | 20 |
| | No. of correspondences perceptions-model | 18 |
| | % of correspondences perceptions-model | 90.0% |
| Municipality no. 3 | Total no. of odour episodes | 20 |
| | No. of correspondences perceptions-model | 18 |
| | % of correspondences perceptions-model | 90.0% |
| Total | Total no. of odour episodes | 89 |
| | No. of correspondences perceptions-model | 77 |
| | % of correspondences perceptions-model | 86.5% |

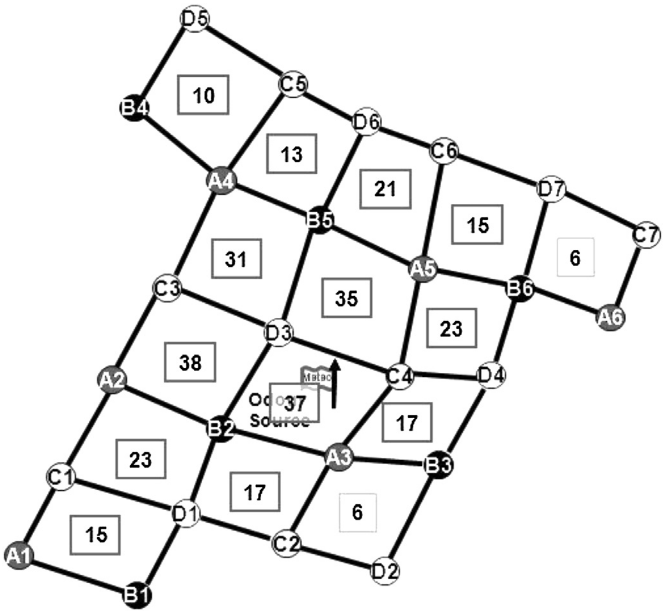


**Fig. 3.** Example of grid method: the study area around the odour source is configured as a grid of measurement points. The odour hour frequency for an assessment square is determined by making repeated single measurements by human panel members at the measurement points that define the corners of the assessment square. The odour hour frequency for the assessment square is calculated as the total number of odour hour test results divided by the total number of measurements at the four points defining an assessment square.

responses are classified in two odour classes: pleasant and not pleasant that also covers the neutral category. Such a differentiation could be useful when dispersion modelling is used to estimate annoyance. In such a case, the distinction of odour types in odour exposure can help interpretation (for example: two potential sources, one with pleasant and another one with unpleasant odour) and then increase the efficiency of the modelling. The advantage of human smelling during field measurement allows the distinction odour/no odour, the potential class pleasant/unpleasant but also a more precise description odour from different plants (e.g., plant A vs. plant B, etc.).

An alternative of short field inspection to know odour exposure can be a questionnaire survey. An example of such approach is described by Claeson et al. (2012). Of course, this approach generally gives important information for odour frequency determination and odour impact assessment purposes, even though the results of a questionnaire survey may be not directly comparable with the outputs of a dispersion model (period of time with different meteorological conditions). The questionnaire covers a large period of time (several days or weeks) but is generally shorter than a grid measurement, typically one year (Guillot et al., 2012). So, because the field inspection based on plume measurement is carried out, for one round, on a short period of time (half a day), the results can be linked with very precise weather conditions and so the efficiency of the model can be tested with less uncertainty.

As an alternative method for measuring ambient odour concentration, or as a complementary approach in addition to the others, field olfactometers can be used to characterize odour levels in an environment. Actually, two main instruments called Nasal Ranger (St. Croix Sensory Inc., USA) and Scentroid SM110 (IDES Canada Inc., Canada) are available on the market. The field olfactometer, a simplified portable dilution device, helps to determine the ambient odour levels and it gives a reading of the odour detection to threshold (Benzo et al., 2012; Brandt et al., 2011b) and therefore may be a useful tool for downwind odour intensity measurement (Pan et al., 2007). During evaluation, the ambient air is filtered through carbon filters attached to the instrument (Nasal ranger) or carbon filtered air from a high pressure compressed air tank (Scentroid SM110), and in both cases, this air is used as dilution air. Globally dilution ratios range from 2 to 200, thereby concerning low odour intensity levels. Thus, such field olfactometers may be helpful to estimate odour concentrations below 50 $ou_E$ $m^{-3}$, for which bag sampling followed by dynamic olfactometry is non-applicable.

## 5. Electronic nose

Another means for measuring odours in the field and determining odour exposure directly at receptors are electronic noses. As

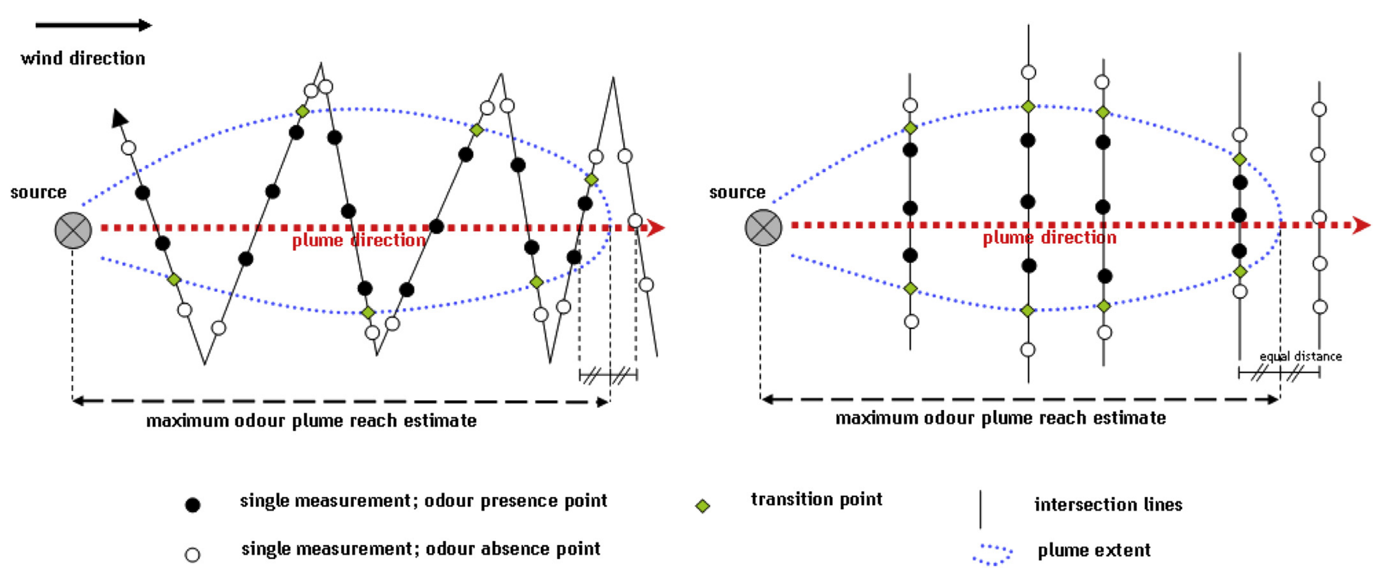


**Fig. 4.** Principle of the plume method: the presence or absence of recognisable odours in and around the plume originating from a specific odour emission source, under specified emission situation and meteorological conditions is determined by a panel of human assessors either by zigzagging and traversing the plume (dynamic approach, on the left), or by being located in specific points on perpendicular axes (static approach, on the right).

a matter of fact, in recent years, the possibility of applying electronic noses for the characterization of environmental odours has become an issue of increasing interest. For this purpose, instruments should be suitable for the continuous analysis of the ambient air at receptors, thereby detecting the presence of odours, and possibly classifying and/or quantifying them, as well.

Moreover, electronic noses could be useful for odour impact assessment purposes in cases where dispersion modelling is hardly applicable. Such cases may include for instance: diffuse sources, such as not ventilated sheds, tanks, caissons, etc., whereby an estimation of the emitted air flow is hardly achieved; or sources having variable emissions over time, whereby it is difficult to associate a given OER to every hour of the simulation time domain, as it is the case for discontinuous productions. In such cases it might be useful to get free from the necessity of minutely characterizing the emission, and to measure exposure to odours directly where their presence is lamented by means of suitable instruments.

The electronic nose is a complex system with a human nose like structure (Pearce, 1997; Sankaran et al., 2012), which can be defined as "an instrument which comprises an array of electronic chemical sensors with partial specificity and an appropriate pattern recognition (PR) system, capable of recognizing simple or complex odours" (Gardner and Bartlett, 1994). The electronic nose doesn't perform a chemical analysis of the analysed mixture, but the partially selective sensor array produces a kind of "olfactory pattern", which can be subsequently classified based on a reference database acquired by the instrument in a previous training phase (Capelli et al., 2008b; Ampuero and Bosset, 2003).

Different sensor typologies can be used in electronic nose systems (Wilson and Baietto, 2009; James et al., 2005). In general, an ideal sensing material to be integrated in an electronic nose should fulfil the following technical requirements: (i) high sensitivity to chemical compounds; (ii) low sensitivity to humidity and temperature; (iii) high selectivity; (iv) high stability; (v) high reproducibility; (vi) high reliability; (vii) short reaction and recovery period; (viii) robust and durable; (ix) easy calibration, and (x) small dimensions (Sankaran et al., 2012).

More in detail, an electronic nose to be used as a tool to assess odour exposure at specific receptors should be capable, after a suitable training phase, to: continuously (or repeatedly) analyse the ambient air; detect the presence of odours; classify odours, i.e. recognize their provenance, and/or quantify them in terms of odour concentration. Such responses may then be compared with the results obtained by application of a mathematical model for the simulation of odour dispersion, even though, in general, electronic nose responses the results deriving from the application of a mathematical model for the simulation of odour dispersion are not directly superimposable (Sironi et al., 2007a).

Electronic nose technology is almost 30 years old (Persaud and Dodd, 1982) and electronic noses are already widely used in several sectors, especially in food control (Peris and Escuder-Gilabert, 2009). However, their application as odour impact assessment tools is still limited, due to a set of technological problems associated with the peculiarities of environmental odour monitoring, requiring outdoor use at far distance from the source. Such problematic aspects include for instance sensor drift over time (Romain et al., 2002); undesired sensor sensitivity to variable atmospheric conditions, e.g. temperature and humidity (Sohn et al., 2008), and the contemporaneous required high sensitivity towards odours for detection at very low concentrations (Dentoni et al., 2012; Nicolas and Romain, 2004).

Nonetheless, in recent years, some works regarding the application of electronic noses for environmental odour monitoring have been published.

One of the first studies aiming to the assessment and quantification of the odour impact from an industrial activity (in this case a composting facility) is described by Sironi et al. (2007b). One electronic nose equipped with 6 thin film metal oxide semiconductor (MOS) sensors was trained to recognize the odours from the plant and then installed at receptors. The study proves the possibility of using the electronic nose as a tool for the continuous monitoring of odours and for odour impact assessment in terms of relative recognition frequency of odours from the monitored plant, thereby pointing out the problem of MOS sensor sensitivity to humidity.

In another study, the same authors tried to compare the results of an odour monitoring campaign by means of electronic noses at a plant for the mechanical and biological treatment of municipal solid waste with the results obtained by application of a mathematical model for the simulation of odour dispersion (CALPUFF) (Sironi et al., 2007a). A qualitative correspondence between model and electronic nose outputs was investigated by verifying that the periods during which the electronic nose installed at a specific receptor detected the presence of odours from the monitored plant correspond to periods in which the simulated odour and pollutants ($H_2S$ and $NH_3$) concentrations at the same receptor were higher with respect to the rest of the monitoring period (Table 3). The results were further compared in a sort of confusion matrix (Kohavi and Provost, 1998), in which the odour concentration values simulated at the receptor by the model are compared with the olfactory classes attributed by the electronic nose to the analysed air (Table 4). This way, the "agreeing" events, i.e. the periods during which the electronic nose detected the presence of odour by attributing the analysed air to an olfactory class different from "neutral air" and the model simulated an odour concentration value at the receptor higher than 0.01 ouE/m3 diagonal of the confusion

**Table 3**
Comparison between electronic nose responses and concentration values simulated by dispersion modelling.

| Date | Hour | Odour conc. ($ou_E\ m^{-3}$) | $NH_3$ conc. ($\mu g\ m^{-3}$) | $H_2S$ conc. ($\mu g\ m^{-3}$) | Olfactory class recognized by electronic nose |
|---|---|---|---|---|---|
| 15/07/2006 | 10.00 | 0.000000000 | 0.000000000 | 0.000000000 | Neutral air |
| 15/07/2006 | 11.00 | 0.000000000 | 0.000000000 | 0.000000000 | Neutral air |
| 15/07/2006 | 12.00 | 0.000000000 | 0.000000000 | 0.000000000 | Neutral air |
| 15/07/2006 | 13.00 | 0.000136628 | 0.001271886 | 0.000129044 | Neutral air |
| 15/07/2006 | 14.00 | 0.000000000 | 0.000000000 | 0.000000000 | Neutral air |
| 15/07/2006 | 15.00 | 0.000000000 | 0.000000000 | 0.000000000 | Bio-stabilized material |
| 15/07/2006 | 16.00 | 0.010202430 | 0.095593530 | 0.009607316 | Bio-stabilized material |
| 15/07/2006 | 17.00 | 0.000167998 | 0.001577853 | 0.000159072 | Bio-stabilized material |
| 15/07/2006 | 18.00 | 0.014274890 | 0.132315600 | 0.013313150 | Bio-stabilized material |
| 15/07/2006 | 19.00 | 0.011994950 | 0.112650000 | 0.011331550 | Bio-stabilized material |
| 15/07/2006 | 20.00 | 0.000139104 | 0.001335324 | 0.000134466 | Neutral air |
| 15/07/2006 | 21.00 | 0.000012130 | 0.000114132 | 0.000011580 | Neutral air |
| 15/07/2006 | 22.00 | 0.000000000 | 0.000000000 | 0.000000000 | Neutral air |

**Table 4**
Confusion matrix relevant to the electronic nose responses and the modelled ground odour concentrations.

| | $c_{od} < 0.01$ $ou_E$ $m^{-3}$ | $c_{od} > 0.01$ $ou_E$ $m^{-3}$ |
|---|---|---|
| Neutral air | 64 | 3 |
| Bio-stabilized material | 5 | 8 |

matrix, are represented by the diagonal of the matrix. A so called "accuracy index" was then calculated as the ratio between the agreeing events and the total events, which turned out to be 90%, thus indicating a quite good qualitative agreement between the two odour impact determination techniques. Differences in the results may be due mainly to the fact that the model does not consider temporary or accidental emission sources.

Other interesting applications of electronic noses as odour impact assessment tools are reported by Nicolas et al. (2012) and by Milan et al. (2012).

In this study of Nicolas et al., a network of 5 home-made electronic noses comprising each 6 metal oxide sensors from Figaro® (Figaro Engineering Inc., Japan) was applied for the assessment of odour annoyance near a compost facility. Each electronic nose detects the odour events and by classifying the odour types into five possible categories corresponding to the facility odour sources and to odour-free air. Then, a quantitative model assesses the "level" of the odour and estimates the odour emission rate at the instrument location. Finally, according to the wind direction, the responses of the electronic noses in the right wind sector are used to assess the maximum downwind distance of odour perception. The study proves the system to be sufficiently efficient to assess possible odour annoyance in the surroundings of the plant, even though the used approach suffers from various uncertainties, from the sensors to the final determination of the distance of downwind annoyance.

The study performed by Milan et al. describes a huge monitoring program aiming to map the odour impact in the Port of Rotterdam by using 40 fixed and 4 mobile electronic noses for a 3-years period and comparing their responses with other sensorial observations (e.g., odour complaints reports and odour observations of experts). The objectives of investigating the electronic nose potential as an odour management tool for reducing odour exposure as well as a safety management tool for a fast recognition of accidental gases resulting in incidents gave promising results, still requiring further development of the knowledge base and incremental improvements to the system.

The above mentioned applications of electronic noses to environmental odour monitoring prove the recent developments in electronic nose technology, thereby pointing out the possibility of employing them as effective field odour measurement tools, even though some technical difficulties still need to be addressed to achieve sufficient measurement accuracy and repeatability.

## 6. Conclusions and future perspectives

This work reviews the techniques that can be adopted for measuring odours in the field and discusses how such techniques can be used in alternative or in combination with odour dispersion models for odour impact assessment purposes, and how the results of field odour measurements and model outputs can be related and compared to each other.

As a matter of fact, different, more or less sophisticated and reliable models are available for simulating the dispersion of odour emissions into the atmosphere, but only few studies concerning specifically odour dispersion modelling validation have been published up to now. Besides, measuring of odours in the field is still an important task, either for directly assessing odour annoyance or for verifying that modelled odour concentrations correspond to the effective odour perception by humans.

Different approaches and techniques can be used for measuring odours in the environment.

Approaches based on chemical measurements of tracer compounds in the environment entail the advantage of being easier and more reliable than the measurement of low odour concentration values by dynamic olfactometry, which has detection limits of about 20–50 $ou_E$ $m^{-3}$, thus limiting the applicability of this sensorial technique to assess ambient air samples around the threshold for nuisance levels. However, the identification and quantification of odour tracer compounds by means of chemical analyses on ambient air samples may not be directly correlated to the odour perception in the environment (Dincer et al., 2006; Dincer and Muezzinoglu, 2007). On one hand, especially in the case of complex sources, it may be difficult to identify and select proper tracer compounds that are responsible for the odour emissions (Capelli et al., 2012a). Moreover, the evaluation of odour concentration or other odour properties based solely on the knowledge of the chemical composition of an odorous mixture entails strong imprecision. For this reason, chemical analysis, despite being a reliable and consolidated technique, in most cases is unsuitable for the purpose of determining the presence of odours in the environment. The only cases for which this kind of analytical approach might be successfully applied include the rare situations where the odour emission is characterized by one single compound, thus resulting that there is a direct proportionality between the analytical concentration of the compound and the odour concentration.

Another possibility for evaluating odour exposure at receptors involves social participation, i.e., collecting and analysing complaints data, administering and analysing one-shot surveys concerning local residents, or questioning resident panellists on repeated occasions or asking them to regularly complete odour diaries. Surveys based on the compilation of suitable questionnaires by the citizens may also be used for comparison with results of odour dispersion modelling, by verifying if the times at which odour is perceived at a certain receptor correspond to higher ground odour concentration values (at least above the odour detection threshold, i.e. 1 $ou_E$ $m^{-3}$) simulated by the model, therefore confirming the applied simulation procedure. There are several experiences proving both the efficacy and the positive psychological effect of involving the population and making them actively take part to odour impact assessment studies. One drawback of relying on the resident population is that their perception of odours might be influenced by their subjectivity, as well as by their experiences and opinions (e.g., stress or even hatred due to odour annoyance, sensitization to specific odours), which may turn out in unreliable responses, in good or in bad faith. As a consequence, the processing of the outcomes derived by such surveys is generally rather complicated, and requires a previous careful screening step for excluding outliers or unreliable responses (Sironi et al., 2010).

One way to partially overcome the problem of the subjectivity is to run field olfactometric surveys with trained human assessors (panellists). Such field inspections allow the determination of ambient air concentration close to the odour detection threshold, and are recently seen as being a more convenient method for odour impact assessment in the field. The growing importance of this method is proved by the recent constitution of a European working group for the draft of a European Standard on odour exposure (Guillot et al., 2012), which should be issued in the very next future. One drawback of field inspections is that they can get rather expensive, especially if the survey is conducted for a prolonged period of time involving a high number of panellists.

At last, another promising approach, which can be successfully applied for odour impact determination in the field, is the use electronic noses. Electronic noses can be used both for detecting and identifying odours in the field, by attributing the analysed air to an olfactory class corresponding to a specific odour source. With respect to other measurement methods involving the use of human assessors (e.g., olfactometry, field inspections), instrumental analysis with electronic noses entails the great advantage of allowing the measurements to be run continuously. Even though the responses of electronic noses are not directly superimposable with the results derived from the application of a mathematical model for the simulation of odour dispersion, both methods can however be compared by evaluating if the events of odour detection by electronic noses at a certain receptor correspond to high odour concentration values simulated by the dispersion model at the same receptor (Sironi et al., 2007a). Despite these advantages, the application of electronic noses as odour impact assessment tools is still limited, due to a set of technological problems such as sensor drift over time, undesired sensor sensitivity to variable atmospheric conditions, and the contemporaneous required high sensitivity towards odours for detection at very low concentrations. Nonetheless, the number of studies facing this kind of problems and describing successful applications of electronic noses for environmental odour monitoring is rapidly increasing in the last years, thus pointing out the growing interest towards this promising technology (Dentoni et al., 2012; Milan et al., 2012).

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