Combination of field inspection and dispersion modelling to estimate odour emissions from an Italian landfill

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ABSTRACT

In the case of landfills, the determination of odour emissions is particularly complex. Up to now, no universally accepted methodology for sampling and assessing emissions from landfill surfaces has been established. Besides, the dependence of such emissions from some crucial environmental variables, such as wind speed, has not been univocally defined yet. In this study, odour dispersion modelling and plume inspections by human assessors were combined in order to estimate the odour emissions from a landfill in Southern Italy. Two substantially different approaches were compared: the one that considers emissions as a function of the wind speed blowing over the surface, counterposed to the one that considers odour emissions as constant, in agreement with the most recent studies on the matter. The comparison of the field assessments and the model clearly highlights that the first approach significantly overestimates the landfill odour emissions, whereas the use of a constant odour emission rate results in a much better correspondence between model outputs and field assessments, both in terms of shape and extension of the determined odour plume extents.

Keywords: odour emission rate; odour impact assessment; plume method; olfactometry; landfill gas; landfill surface emissions
1. INTRODUCTION

Since several decades now, odours are, among atmospheric pollutants, the major cause of population’s complaints to local authorities in many different contexts (Brambilla & Navarotto 2010; Hayes et al., 2014; Henshaw et al., 2006). Odour pollution is nowadays a serious environmental (and in some cases also health) concern (Claeson et al., 2013), and is currently subjected to specific regulation in many countries (Loriato et al., 2012; Sironi et al., 2013; Brancher et al., 2017).

The existence of regulatory acceptability criteria entails the necessity to develop suitable methods for odour assessment, debunking the common belief that odour characterization is more art than science (Lucernoni et al., 2017a; Muñoz et al., 2010).

One of the odour impact assessment techniques that is most commonly applied and contemplated by different regulations involves the use of the odour emission rate (OER), expressed as unit of odours emitted per unit time, combined with topographic and meteorological data of the site, as input data for dispersion models, which allow to estimate how odour emissions are diluted and transported into the atmosphere (Capelli et al., 2013a; Brancher et al., 2017). The assessment of the OER relevant to an odour source typically involves 3 phases: on-site sampling (Bockreis & Steinberg, 2005; Capelli et al., 2013b), sample analysis (CEN EN 13725, 2003), and data elaboration for the evaluation of a representative OER (Hudson et al., 2009; Capelli et al., 2013b).

In the specific case of area sources, for which sampling is typically conducted by means of fluxed hoods (Bockreis & Steinberg, 2005; Capelli et al., 2013b), with the odour concentration it is possible to evaluate the Specific Odour Emission Rate (SOER), that is the odour units emitted from the source per surface and time unit [ou/m²/s] referred to the specific operating conditions used during sampling (Hudson et al., 2007; Capelli et al., 2009). Specific models are then required in order to relate the SOER to real field conditions (Lucernoni et al., 2017b).
In the case of landfills, the determination of odour emissions (in terms of OER or SOER) is particularly complex. Even assuming that the emissions of odour is mainly associated with the unwanted emission of landfill gas (LFG) that escapes the LFG collection system (Capelli et al., 2008; Chemel et al., 2012; Saral et al., 2009), up to now, no universally accepted methodology for sampling and assessing LFG emissions from landfill surfaces has been established (Babilotte et al., 2010; Fredenslund et al., 2010; Lohila et al., 2007; Lucernoni et al., 2016a, 2017c; Mackie et al., 2009). Besides, the dependence of such emissions from some crucial environmental variables has not been univocally defined yet, making the quantification of LFG emissions for implementation in a dispersion model hardly applicable. If on one hand the dependence of the OER from the wind speed for other types of area sources such as liquids has been studied and verified experimentally (Capelli et al., 2009; Lucernoni et al., 2017b), proving that the OER is proportional to the speed of the wind blowing over the surface with an exponent of 0.5 (in case of laminar flow) or 0.78 (in case of turbulent flow), recent studies seem to point out that landfill surfaces need to be treated differently (Lucernoni et al., 2016b). As a matter of fact, the mechanism that regulates emissions from landfill surfaces is not forced convection but the presence of an endogenous gas flow due to the formation of LFG inside the landfill body, which is not directly affected by the wind blowing over the surface (Lucernoni et al., 2017a).

The effects of the other environmental parameters mentioned in other studies has never been really quantified up to now; on the contrary, the statements found in literature about the dependence of LFG emissions on variables such as atmospheric temperature or soil humidity are sometimes contradictory (Lucernoni et al., 2016c, Park et al., 2001; Rachor et al., 2013)

In a recent study, we tried to investigate and compare different approaches to estimate odour emission rates from landfill surfaces (Lucernoni et al., 2017a). Thanks to the consolidated experience regarding the odour impact of this particular landfill acquired over the years, it was possible to conclude that the most reliable methods for the estimation of odour emissions from the landfill surface involve measurement campaigns in the field with a tailored sampling hood system, either Flux Chamber or Static Hood. The use of a Wind Tunnel showed an overestimation of the landfill OER, due to the fact that the emission is considered as a function of the wind speed over the emitting surface, as it is for quiescent passive sources (Lucernoni...
et al., 2017b), whereby for landfills the assumption of such dependency is groundless, since the driving force of the emission phenomenon is not forced convection. However, as stated in the above mentioned study, the evaluation of the best method for odour emission sampling is lacking of a specific validation in the field. In general, 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 a quite complicated task (Capelli et al., 2013a).

For this reason, the attempt to validate odour dispersion models often entails the adoption of very specific techniques (Gebicki et al., 2016), either sensorial, involving the “use” of human assessors in the field (Dentoni et al., 2013; Nicell, 2009), or instrumental, such as chemical analyses or electronic noses (Capelli et al., 2014; Szulczyński et al., 2017).

In this study we decided to combine odour dispersion modelling and field assessments by human assessors with the technique of the plume inspection (CEN, 2016; Guillot et al., 2012) in order to estimate the odour emissions from a landfill in Southern Italy. The estimation was based on the comparison of the model outputs obtained with different OER values and the registration of odour perceptions around the landfill by a panel of trained assessors. This comparison allowed to evaluate the values for the SOER, which result in a better correspondence between the outcomes of the field inspection and the odour impact simulated by the model during the field inspections.

The different SOER values considered for this study are derived basically from two different approaches: the one that considers the odour emissions as independent from the wind speed over the landfill surface, in agreement with the most recent studies on the matter (Lucernoni et al., 2016b), and the one that treats the landfill as a fully passive area source, thereby considering the SOER as a function of the wind speed blowing over the surface. This second approach, although not having any scientific justification, is the one contemplated by the regional guideline on odour emissions in the region where the studied landfill is located. The same problem applies also for other regions in Italy, where the same methodology is foreseen by the local regulations in matter of odour emission control (Regione Lombardia, 2012).
2. MATERIALS AND METHODS

2.1 Description of the case study

The study was conducted at a landfill located in Southern Italy, and more precisely in the Region of Puglia, close to the city of Taranto. Taranto has an extensive industrial area, comprising a steel plant, an oil refinery, and the studied landfill, as shown in Figure 1.

Figure 1. The city of Taranto and its industrial area comprising a steel plant (red), an oil refinery (blue), and the studied landfill (green)

The proximity of the industrial area to the town north-western boundary is the origin of several odour complaints, which makes that both people living in this area and local authorities are very attentive to odour pollution problems.

On this background it was decided to carry out a specific study in order to evaluate the odour impact of the landfill on the surrounding areas.
This study has a first objective to apply a “plume method” field inspection in order to determine the presence or absence (yes/no) of recognizable odours coming from the studied landfill, thereby evaluating the plume extent present at the time of the field inspection by identifying the “transition points” from odour absence to odour presence or vice versa (CEN, 2016).

After this evaluation, the study has the primary aim to compare the results of the field investigation with the outcomes of a set of atmospheric odour dispersion simulations referred to the periods of execution of the field inspections. This allows to evaluate the SOER values and the hypotheses regarding the SOER constancy or dependency from the wind speed that result in a best fit between simulated odour impact and plume extent determined by field inspection.

The reason behind this work is the necessity to experimentally verify the thesis proposed in some recent scientific publications highlighting the different volatilization mechanism regulating emissions from landfill surfaces compared to passive liquid area sources, where forced convection is the driving force for emission.

The regional guideline of the Region of Puglia (where the studied landfill is located) indicates the use of wind tunnels for odour sampling on landfill surfaces and the recalculation of the SOER (and thus of the OER) as a function of the wind speed, according to the following relationship, which is valid for passive liquid area sources (Capelli et al., 2009; Capelli et al., 2013b):

\[ \text{SOER}, \text{OER} \propto v^{1/2} \]

On the contrary, the most recent studies on the matter (Lucernoni et al., 2016b) highlight the need to consider the SOER independent from the wind speed, because of the absence of a direct correlation between wind speed and emission from landfill surfaces (Lucernoni et al., 2017a).

### 2.2 Field inspection

#### 2.2.1 The dynamic plume method

Two different types of inspections with human assessors for the determination of odour in the field can be used: the grid (CEN, 2016b) and the plume method (CEN, 2016a). In both cases, human panel members
characterize an area by the presence or absence of an odour. Grid method is a long period (one year) statistical survey method to obtain a representative map of a recognizable odour exposure over a selected area, whereas the plume method is a short period experiment (several times of approximately half a day under meteorological conditions) to determine the extent of recognisable odour from a specific source (Capelli et al., 2013c).

The plume method, allowing the direct determination of the extent of the downwind odour plume under defined meteorological conditions, which can be compared with the extent of the odour plume obtained by dispersion modelling, is clearly the most appropriate method for the particular scope of this study, i.e. the “backward” estimation of a source emissions.

More in detail, we decided to apply the dynamic plume method, whereby the panel members cross the plume following a zigzag direction: by successively entering and exiting the plume the transition between absence and presence of recognizable odour is determined, and thus the extent of the plume is defined (Figure 2).

The EN defines that for this type of investigation a minimum number of 2 assessors shall be employed, and that each survey involves the evaluation of a minimum of 20 points, and the determination of at least 6 transition points.

Figure 2. Schematic diagram of an example of dynamic plume measurement (source EN 16841:2016-2)
2.2.1 Design of the field surveys

As already mentioned, for the specific scope of this study, the dynamic plume field inspection method was identified as the most suitable method to “validate” the outputs of the dispersion modelling study and thus go back to the estimation of the landfill effective odour emission rate. However, the normalized method described in the previous paragraph had to be slightly modified and re-adapted to the specific geographical characteristics and logistics of the investigated area.

A preliminary inspection survey was organized inside the landfill and in the surrounding areas in order to map the whole investigation area in detail and identify the paths that can be covered by the panel members in order to identify the presence of odours from the landfill.

As a first step, the areas surrounding the landfill were inspected thoroughly during a preliminary survey, with the aim of identifying the walkable paths for the panel to be used during the field inspections in order to identify the presence of odours coming from the landfill.

Given the big dimensions of the landfill and thus of its surrounding area, in order to design the field inspection surveys properly, it was decided to identify 4 different sub-areas located North, South, East and West of the landfill, respectively, to be inspected depending on the wind direction during the measurement cycles. As an example, if before the start of the field inspection a wind blowing from North to South is registered, then the measurement will take in the sub-area located South of the landfill.

The 4 sub-areas were inspected thoroughly by foot and by car, with the aim of tracing paths along which the panel may zig-zag cross the plume, compatibly with the shape of the area to be investigated and the presence of inaccessible areas (e.g., other properties, other plants, railway). This inspection was carried out by using GPS geo-localisation systems in order to transfer the acquired data and trace the paths on common mapping systems such as Google Earth.

The identified paths are illustrated in Figure 3, together with the limits of the inaccessible areas.
As a general rule, plume inspections shall have a limited duration, in order on one hand to keep a high attention level of the assessors, and on the other hand to avoid that meteorological conditions vary significantly during the inspection. This latter aspect is crucial considering that the aim of the investigation is to evaluate the plume extent, which is clearly highly dependent on the specific meteorological conditions. Because of this requirement about the inspection duration and the high distances involved (as can be derived from the scale in Figure 3 each path is at least 2 km long), the assessors were equipped with bicycles, in order to accelerate the movements along the paths and thus maintain the duration of each inspection within a reasonable interval (i.e. 1.5-2 hours). The possibility to use bikes is mentioned in the EN 16841:2016.

For similar reasons, the panel was divided into 2 groups, each composed by a minimum of 2 people: this allows to extend each inspection to 2 of the paths indicated in Figure 3, in cases when two paths are downwind. As an example, when the wind blows from South-West to North-East, both the blue (North) and
the green (East) paths will need to be inspected. Those paths are not connected since there is the railway between them, thus making it necessary to have two separated groups inspecting each path.

As already mentioned, due to the dependence of the plume extent on the meteorological conditions, it is important that conditions remain stable for the whole duration of the inspection, thus it is necessary to avoid to carry out the field inspections during periods when meteorological conditions are typically unstable, for instance due to thermal inversion, i.e. sunset or sunrise.

Since the aim of this study is the evaluation of the most suitable method to characterize odour emissions due to landfill gas emissions through the landfill surface, the surveys were designed as to be conducted in those periods when the only source of odour is landfill gas, and no other interfering sources are present. Considering that the studied landfill is active, this means that the surveys need to be carried out during the times of the day when the fresh waste conferred to the landfill is covered, and thus the emissions from fresh waste tipping is negligible.

For this reason, it was decided to carry out the field inspection during the following periods:

- Early morning, before fresh waste conferring, i.e. between 6.30 am and 8.30 am
- Afternoon, after covering of the daily conferred waste, but before sunset, i.e. between 5 pm and 7.30 pm
- Night, after sunset, i.e. after 9.30 pm.

Besides the interference of the fresh waste conferring, which could be avoided by choosing the survey times properly as described above, further interferences may be caused by the presence of other plants originating odour emissions close to the studied landfill, i.e. the steel plant and the oil refinery, as shown in Figure 1. In order to minimize the possibility of interference, a training of the panel members was carried out daily prior to the field inspection. During the training, the panel members sniffed different odour samples of landfill gas collected over the landfill surface at different concentrations in order to get used to the specific odour to be recognized during the field inspection and thus be able to distinguish it from the presence of other odours. In this case, the elimination of interferences with other odours was made
possible by the fact that the emissions from the steel plant and from the oil refinery have a completely
different odour character from the landfill gas odour, and can therefore be easily discriminated after a
suitable training phase.

2.2.2 Execution of the field inspection surveys

The field inspection surveys were programmed in the period between Monday, 10\textsuperscript{th} April 2017 and
Wednesday, 12\textsuperscript{th} April 2017, involving 6 measurement cycles. The choice to carry out a limited number of
measurement cycles is connected to the main objective of the study: in this case the primary aim of the
field inspection was not the characterization of the plume extent by itself, but the field inspection was only
functional for the evaluation of the most suitable method to estimate odour emissions from a landfill
surface, by comparison of the field assessments carried out under specific meteorological conditions with a
simulated odour impact.

Each cycle was carried out by 3 experienced assessors, one accompanying person and a measurement
leader, the latter having the function to coordinate the measurement, decide the inspection paths and
conduct the panel along them, and collect the filled measurement forms and the GPS registrations. The
assessors were 3 girls aged between 21 and 27 selected according to the criteria for panel selection
described in the EN 13725:2003 for dynamic olfactometry.

As previously mentioned, for each measurement cycle the panel was divided into two groups (one group
composed by one assessor and one accompanying person/coordinator, and the other group by two
assessors and one accompanying person/coordinator, respectively), in order to make it possible to
investigate 2 of the paths indicated in Figure 3 during each measurement cycle.

A summary of the measurement cycles, reporting date and hour of the measurement, observed wind
direction and the areas inspected is shown in Table 1. It is worth to mention that the week of the
inspections was characterized mainly by wind calms or by the presence of very weak winds.
During each measurement cycle, all assessors and accompanying person/ coordinator were equipped with a map of the landfill indicating the 4 inspection paths (Figure 3), where they had to indicate the measurement points, as well as with a GPS system, in order to register their position at any moment of the measurement cycle. At each measurement point, the assessors were asked to fill in a specific form, in which they had to indicate the presence or absence of odours, and the type of perceived odour.

### 2.3 Sampling on the landfill surface

In order to allow the comparison of the two main different approaches that can be adopted in order to evaluate odour emissions from landfill surfaces – i.e. the one that considers the odour emissions as independent from the wind speed over the landfill surface, and the one that treats the landfill as a fully passive area source thus considering the SOER as a function of the wind speed over the surface – olfactometric sampling was carried out by using a wind tunnel, which is the sampling method that is typically used for odour sampling on passive area sources contemplated. The wind tunnel used for the study, which is in conformity with the regional guideline on odour emissions in the region of Puglia (where the landfill is located), is the same as described by Capelli et al. (2009). A scheme is shown in Figure 4. A neutral air flow from a synthetic air bottle is flown into the wind tunnel at a flow rate of 2500 l h⁻¹, which corresponds to a sweep air velocity inside the central body of the wind tunnel of about 0.035 m s⁻¹.

### Table 1. Summary of the measurement cycles

<table>
<thead>
<tr>
<th>Measurement cycle</th>
<th>Date</th>
<th>Time of the day</th>
<th>Landfill activity</th>
<th>Cycle start hour</th>
<th>Cycle end hour</th>
<th>WD (observed)</th>
<th>Groups/ paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>10/04/2017</td>
<td>Afternoon</td>
<td>After waste covering</td>
<td>17:00</td>
<td>19:00</td>
<td>SW</td>
<td>Group A - EAST path Group B - NORTH path</td>
</tr>
<tr>
<td>II</td>
<td>11/04/2017</td>
<td>Morning</td>
<td>Before waste arrival</td>
<td>7:00</td>
<td>8:30</td>
<td>N</td>
<td>Group A - NORTH path + SW perimeter Group B - WEST path + N perimeter</td>
</tr>
<tr>
<td>III</td>
<td>11/04/2017</td>
<td>Afternoon</td>
<td>After waste covering</td>
<td>18:00</td>
<td>19:30</td>
<td>W</td>
<td>Group A - SOUTH + EAST paths Group B - NORTH + EAST paths</td>
</tr>
<tr>
<td>IV</td>
<td>12/04/2017</td>
<td>Morning</td>
<td>Before waste arrival</td>
<td>6:30</td>
<td>8:15</td>
<td>NW</td>
<td>Group A - NORTH path + perimeter Group B - NORTH path</td>
</tr>
<tr>
<td>V</td>
<td>12/04/2017</td>
<td>Afternoon</td>
<td>After waste covering</td>
<td>17:30</td>
<td>18:40</td>
<td>NE - _</td>
<td>Group A+B - EAST path</td>
</tr>
<tr>
<td>VI</td>
<td>12/04/2017</td>
<td>Night</td>
<td>After waste covering</td>
<td>21:45</td>
<td>22:40</td>
<td>N?</td>
<td>Group A+B - Internal + external perimeter</td>
</tr>
</tbody>
</table>
Olfactometric sampling over the landfill surface was carried out simultaneously with the field inspection, in order to make the odour measurements comparable to the field assessments.

In the case of wind tunnel measurements, the SOER is then calculated as (Capelli et al., 2013b):

\[
SOER = \frac{c_{od} \cdot Q_{air}}{A_{base}}
\]

Where SOER is the Specific Odor Emission Rate (ouE m\(^{-2}\) s\(^{-1}\)), \(c_{od}\) the measured odor concentration (ouE m\(^{-3}\)), \(Q_{air}\) the air flow rate inside the hood (m\(^{3}\) s\(^{-1}\)) and \(A_{base}\) the base area of the wind tunnel (m\(^{2}\)). The SOER value is the one that can be used as input parameter for dispersion modelling.

At the moment of the measurements, the studied landfill had a temporary cover, since it was still active. The sampling points were distributed all over the landfill surface, trying to collect samples representative of the whole landfill, despite the small surface covered by the wind tunnel (i.e. 0.125 m\(^{2}\)).

### 2.4 Odour dispersion modelling

The dispersion of the odour emissions from the landfill surface was evaluated using the CALPUFF (California Puff Model) model (Scire et al., 2000). CALPUFF is a multilayer, multispecies, non-steady-state, puff dispersion model. It is able to account for the effects of time and space variations, meteorological conditions (3D met model), on pollutants transport, transformation, and removal (Romeo et al., 2017).

CALPUFF is a transport and dispersion model that represents a continuous plume as a number of discrete packets of pollutant material and evaluates the contribution of a puff to the concentration at a receptor by a “snapshot” approach. Each puff is “frozen” at particular time intervals (sampling steps). The
concentration due to the “frozen” puff at that time is computed (or sampled). The puff is then allowed to move, evolving in size, strength, etc., until the next sampling step. CALPOST is used to process the files from CALPUFF, producing a summary of the simulation results in tabulated forms (de Melo et al., 2012; Wang et al., 2006).

One of the main advantages of the CALPUFF dispersion model compared to Gaussian models is that it is able to treat wind calms (Regione Lombardia, 2012; Barclay and Borissova, 2013), which is particularly important for the case under study, where weak or calm wind conditions were registered during the measurement campaigns. Moreover, other studies prove Gaussian models to significantly overestimate concentrations, especially during stable atmospheric conditions (Dresser and Huizer, 2011; Busini et al., 2012).

The meteorological data used for the study are 3D hourly data processed by means of the WRF (Weather Research and Forecasting) model with 1 km resolution relevant to the studied area relevant to April 2017, including temperature, wind speed, wind direction, solar radiation, relative humidity and rainfall.

The CALMET pre-processor was used as meteorological model to produce the hourly wind and temperature fields, scaling down from the 1-km-resolution of the WRF model to the 3D-gridded modelling domain.

The meteorological domain and the simulation domain were set equal, comprising an area of 6000 m x 6000 m, with a resolution of 100 m, giving a total of 3600 horizontal cells. The dimensions of the horizontal simulation grid were chosen as to include the closest receptors. 10 cells were considered on the vertical plane (Figure 5), giving a total of 36000 cells considered for the study.
Terrain elevations and land use of the studied area were considered in the model in order to build the 3D wind field by means of the GEO pre-processor provided with the GUI of the software used. For the terrain files, the library SRTM1 Version 3 (Global ~30m) was used, whereas the Land Use Files come from the library CORINE CLC2006 – (Europe 100m). The graphical outputs of the terrain profiles and of the land uses relevant to the studied area are provided in the supplementary material.

The CALMET pre-processor also calculates the micrometeorological variables, i.e. surface heat flux, friction velocity, Monin-Obukhov length, convective velocity scale and mixing height that are used to evaluate turbulence. Dispersion coefficients are thus obtained from turbulence parameters computed from micrometeorology instead of being calculated from the Pasquill-Gifford-Turner stability classes, so that they are described by continuous functions, not discrete ones.

The SOER values, expressed in $ouE \cdot m^{-2} \cdot s^{-1}$, derived from the sampling campaigns carried out on the landfill surface simultaneously to the field inspection surveys were used as emission data.

The use of odour concentration and of odour emission rates as inputs for odour dispersion modelling is widely documented in the scientific literature (e.g., Hayes et al., 2006; Piringer et al., 2007; Sheridan et al., 2004; Yu et al., 2010) and it is foreseen as the preferred regulatory approach in different odour regulations worldwide (Brancher et al., 2017; Capelli et al., 2013a). The specific application of the CALPUFF model to
odour emissions for the evaluation of odour impacts in terms of odour concentration (i.e. ouE m⁻³) on the territory is also described in some recent research papers (e.g., Badach et al., 2018; Ranzato et al., 2012; Sironi et al., 2010).

3. RESULTS

3.1 Results of the field inspection surveys

The results of the field inspection surveys were processed by combining the information contained in the forms filled by the assessors with the traces of the paths covered registered by means of the GPS systems. For each measurement cycle, first the significant measurement points were reported on a map (Google Earth), thereby indicating with different colours the points where the presence of recognizable odours coming from the source under investigation (i.e. LFG odour from the landfill) was perceived (red pin), those where the presence of recognizable odours coming from the source under investigation was not perceived (white pin), and those where the recognition of odours was uncertain, meaning that the perceived odour was so weak or sporadic that it was hardly recognizable (yellow colour). As an example, Figure 6 shows the map of the inspection points resulting from the II measurement cycle, carried out in the morning of April, 11.
Second, the transition points, corresponding to the limit of the recognizable odour plume under investigation, were identified on the map as the points halfway between the last absence point (white pin) and the first presence point (red pin). Finally, the transition points were connected by means of an interpolation polyline that identifies the plume extent area, i.e. the extent of the area in which the presence of landfill gas odour from the investigated landfill was recognizable by the assessors.

As an example, Figure 6 shows the map of the inspection points resulting from the II measurement cycle, carried out in the morning of April, 11, and the corresponding plume extent limits (Figure 7).
During the nightly measurement cycle (VI cycle), odour perceptions by the assessors were so limited and sporadic, even in proximity of the source (i.e. on the internal perimetral road), that it was not possible to identify a sufficient number of transition points and thus to trace a line corresponding to the limits of the plume extent. This particular situation is also confirmed by the dispersion model run corresponding to this measurement cycle, as will be shown later in this paper (Figure 20).

### 3.2 Evaluation of the landfill SOER

Table 2 reports the results of the olfactometric analyses carried out on the samples collected on the landfill surface during the field inspections by means of the wind tunnel (Figure 4). Sample no. 3 collected on the first day (April 10, 2017) clearly represents an outlier, since its odour concentration is about one order of magnitude higher compared to the other samples. This can be explained by assuming that the sample was taken over an anomalous emitting portion of the surface, presumably in correspondence of a crack in the landfill cover that allowed a higher landfill gas flow to be emitted into the atmosphere.
Except from this anomalous value, the other odour concentrations measured on the landfill surface are quite similar, adding to the assumption that the collected samples can be considered to be sufficiently representative of the studied landfill. As a matter of facts, although hood methods are widely used for the characterization of emissions from landfill surfaces, they are known to lack of representativeness, especially when huge surface areas are involved, since the surface portions covered by the sampling hoods is typically very small. In such cases, other indirect methods for the determination of emissions can be applied (Babilotte et al., 2010), although such indirect methods usually are very complex and also entail bigger measurement uncertainties compared to hood methods.

The average odour concentration resulting from the experimental measurement campaigns over the landfill surface, which is calculated as the geometric mean of the odour concentration values reported in the last column of Table 2, is $45 \text{ ouE m}^{-3}$. This corresponds to a SOER of $0.25 \text{ ouE m}^{-2} \text{s}^{-1}$. This SOER value is referred to the operating conditions of the wind tunnel as described in par. 2.3, i.e. to a sweep air flow of $2500 \text{ l h}^{-1}$, corresponding to a sweep air velocity if $0.035 \text{ m s}^{-1}$, as provided by the regional guideline.
In the case of liquid area sources, the SOER shall be considered as a function of the wind speed due to the mechanism that regulates the emission from the liquid surface to the atmosphere, i.e. forced convection (Capelli et al., 2009; Lucernoni et al., 2017b). More in detail, the relationship between SOER and wind speed can in most cases be simplified as the SOER being proportional to the square root of the wind speed (Bliss et al., 1995; Capelli et al., 2013b), thus giving:

\[ \text{SOER}_{v_2} = \text{SOER}_{v_1} \left( \frac{v_2}{v_1} \right)^{\frac{1}{2}} \]

Where \( v_1 \) is the air speed during the sampling conditions – in our case corresponding to 0.035 m/s – while \( v_2 \) is the wind speed at a specific hour of the simulation time domain (Lucernoni et al., 2017a).

<table>
<thead>
<tr>
<th>Date</th>
<th>Sample no.</th>
<th>Description</th>
<th>( c_{od} ) [ouf/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/04/2017</td>
<td>1</td>
<td>Wind I 3</td>
<td>29</td>
</tr>
<tr>
<td>10/04/2017</td>
<td>2</td>
<td>Wind I 5</td>
<td>18</td>
</tr>
<tr>
<td>10/04/2017</td>
<td>3</td>
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<td>Wind I 24</td>
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Table 2. Results of the olfactometric measurements relevant to the samples collected on the landfill surface with the wind tunnel method.
Consequently, for odour dispersion modelling purposes, the SOER needs to be re-calculated at the actual wind speed values for every hour of the simulation domain according to this equation.

It is important to highlight that the velocity term in the above equation should not be the wind speed that is conventionally measured at 10 m above ground, which would produce a significant over-estimation of the SOER, since the air velocity that produces the volatilization effect from the emitting surface is not the wind speed at 10 m height, but rather the wind speed over the ground, presumably at a height corresponding to the mean surface roughness over the ground (Lucernoni et al., 2017a).

Different models can be applied in order to re-calculate the wind speed at different heights. One innovative model sources has been recently developed specifically for liquid area sources by Lucernoni et al. (2017b). However, this model not only is specific for liquids, but it entails the necessity to know the chemical nature of the volatilized compounds, and still requires validation, so it wasn’t applied for this study.

Instead, it was decided to rely on the more consolidated “Power Law” model, which is obtained empirically starting from a known wind velocity at certain height \( v_{w}^{h2} \) at height \( h2 \) the height corresponding to the desired wind velocity \( v_{w}^{h1} \) at height \( h1 \), and a so-called Hellman’s parameter (\( \alpha \)) that depends on terrain and stability class (Cook, 1997; Lucernoni et al., 2017a):

\[
v_{w}^{h1} = v_{w}^{h2} \times \left( \frac{h1}{h2} \right)^{\alpha}
\]

### 3.3 Comparison of model outputs and field assessments

Once the results of the field inspection surveys were processed as discussed in section 3.1, these were compared with the outputs of the dispersion modelling applied to the odour emissions referred to the same periods of execution of the measurements cycles (Table 1). This comparison was made possible by superimposing the lines defining the limits of the plume extents resulting from each measurement cycle (as the one shown in Figure 7) on the maps resulting from the odour emission dispersion simulations. More in detail, the simulation maps represent the odour concentrations relevant to the simulation period, which
coincides with the field inspection measurement cycle period, increased by a “peak-to-mean” factor of 2.3,
meaning that the mean values are multiplied by a factor that accounts for peak oscillations around the
mean value of concentration over 60 minutes (Schauberger et al., 2012; Sironi et al., 2010), as provided by
the regional guideline in matter of odours.

3.3.1 Comparison of field assessments and model outputs considering a variable SOER with the wind speed

In order to evaluate the compliance between the odour impact determined experimentally in the field
(field inspections) and the odour impact modelled by application of the first approach for the re-calculation
of the SOER as a function of the wind speed, Figure 8 - Figure 12 compare the plume extents determined by
the 5 field inspection (violet lines), respectively, with the corresponding maps resulting from dispersion
modelling obtained for the same period considering a SOER of 0.25 ouE m\(^{-2}\) s\(^{-1}\) variable with the wind speed
(proportional to \(v^{1/2}\)), according to the “Power Law” described in section 3.2.

The map relevant to the VI measurement cycle is not shown, because odour perception by the assessors
was so weak that it was not possible to determine the plume extent, as will be shown in the next section.
Figure 8. Comparison between plume extent determined by I field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 auE m⁻² s⁻¹ variable with the wind speed (proportional to v¹/²).

Figure 9. Comparison between plume extent determined by II field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 auE m⁻² s⁻¹ variable with the wind speed (proportional to v¹/²).
Figure 10. Comparison between plume extent determined by III field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 ouE m$^{-2}$ s$^{-1}$ variable with the wind speed (proportional to $v^{1/2}$).

Figure 11. Comparison between plume extent determined by IV field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 ouE m$^{-2}$ s$^{-1}$ variable with the wind speed (proportional to $v^{1/2}$).
Figure 12. Comparison between plume extent determined by V field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 ouE m$^{-2}$ s$^{-1}$ variable with the wind speed (proportional to $v^{1/2}$)

3.3.2 Comparison of field assessments and model outputs considering a constant SOER

A similar comparison was done in order to evaluate the agreement between experimentally determined odour impact and the odour impact modelled by application of the second approach that considers the SOER as a constant with the wind speed, thus using a constant SOER value of 0.25 ouE m$^{-2}$ s$^{-1}$ as obtained from the wind tunnel measurements on field.

Therefore, Figure 13 - Figure 17 show the comparison maps with the plume extents determined by the 5 field inspections (violet lines, same as in Figure 8 - Figure 12), respectively, superimposed to the maps obtained from application of the dispersion model for the same period by choosing a constant SOER value of 0.25 ouE m$^{-2}$ s$^{-1}$.

All the comparisons between field assessments and model outputs are dependent on the specific model settings and conditions: one important modelling condition that should be considered in order to evaluate
the correspondence between model outputs and the odour impact assessed in the field, is the use of a constant peak-to-mean factor of 2.3, as will be discussed in the following section.

**Figure 13.** Comparison between plume extent determined by field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 \( \text{ou}_2 \text{ m}^{-2} \text{ s}^{-1} \) constant with the wind speed
Figure 14. Comparison between plume extent determined by II field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 auE m$^{-2}$ s$^{-1}$ constant with the wind speed.

Figure 15. Comparison between plume extent determined by III field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 auE m$^{-2}$ s$^{-1}$ constant with the wind speed.
Figure 16. Comparison between plume extent determined by IV field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 ouE m\(^{-2}\) s\(^{-1}\) constant with the wind speed.

Figure 17. Comparison between plume extent determined by V field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of 0.25 ouE m\(^{-2}\) s\(^{-1}\) constant with the wind speed.
4. DISCUSSION

4.1 Evaluation of the comparison of model outputs and field assessments

Based on the comparison of the field assessments and the model outputs obtained by considering the landfill SOER as a function of the wind speed (Figure 8 - Figure 12), it is evident that this approach significantly overestimates the landfill odour emissions. In Figure 8 - Figure 12 it is clearly visible that the simulated odour impact results in odour concentrations that are almost one order of magnitude higher than those determined in the field by a panel of trained and expert assessors.

On the contrary, the comparison of the model simulations based on a constant SOER, independent from the wind speed (Figure 13 - Figure 17) shows a better correspondence between model outputs and field assessments, in terms of shape and extension of the determined odour plume extents.

In order to optimize the correspondence between a further step was made: considering that the odour concentration at which the assessors are able to recognize the presence of odours in the field corresponds to the so called “odour recognition threshold”, which lies around 2-3 ouE m\(^{-3}\) (Denti et al., 2013), the SOER value used as input parameter for the dispersion model was varied from the value of 0.25 ouE m\(^{2}\) s\(^{-1}\) obtained from the wind tunnel measurements on field as to best fit the field inspection results.

According to this procedure, the SOER value that results in a best correspondence between model outputs and odour impact determined during the field measurement cycles I, III and V (Figure 13, Figure 15 and Figure 17, respectively) wasn’t varied: with a constant SOER of to 0.25 ouE m\(^{2}\) s\(^{-1}\) a very good fit is already obtained, resulting in a plume extent determined by the field inspection very close to the modelled iso-concentration lines corresponding to 2-3 ouE m\(^{-3}\).

Instead, as can be seen from Figure 14 and Figure 16, the use of a constant SOER of to 0.25 ouE m\(^{2}\) s\(^{-1}\) results in a slight overestimation of the modelled odour impact, since the lines delimiting the plume extents determined by field inspection fall over the iso-concentration lines corresponding to odour concentrations of about 5-7 ouE m\(^{-3}\). For this reason, the SOER values used for dispersion modelling had to be reduced to 0.07 and 0.1 ouE m\(^{2}\) s\(^{-1}\), respectively, in order to obtain a “best fit” (Figure 18 and Figure 19).
Also the “best fit” SOER values are referred to the specific model settings and conditions, i.e. in this specific case, the use of a constant peak-to-mean factor of 2.3. The effect of the peak-to-mean factor on the comparisons between field assessments and model outputs will be discussed in the following section.

Another reason why the SOER value of 0.25 ouE m\(^{-2}\) s\(^{-1}\) determined based on the WT measurements over the landfill surface (section 3.2) is possibly overestimated can be explained looking at the olfactometric measurement results reported in Table 2. Indeed, the SOER value of 0.25 ouE m\(^{-2}\) s\(^{-1}\) comes from the average odour concentration of 45 ouE m\(^{3}\) calculated from the odour concentration values reported in Table 2. In general, the odour concentration values measured in the samples collected with the WT over the landfill surface are so low that they are likely to be not representative exclusively of the characteristic odour of the LFG emitted through the landfill surface, but it is likely that at least a share of the sample concentration value is given by the so-called background odour. In this situation, the background odour is intended as the odour of the landfill surface itself and of its components (e.g. soil, grass, sand...), odour that contributes to the overall concentration value of the collected sample, but is not representative solely of the emitted LFG odour. There are literature references identifying typical background odour concentrations from 5 to 60 ouE/m\(^{3}\) (UK Defra, 2010) or the intrinsic lower detection limit for Dynamic Olfactometry as 20-50 ouE/m\(^{3}\) (Capelli et al. 2013a).

This is why the application of this direct approach by means of WT for the evaluation of the OER from sources that are not highly odorous such as landfill surfaces may result in an overestimation of the real emissions and the real impact (Lucernoni et al., 2016c).
Figure 18. Comparison between plume extent determined by II field inspection (violet line) and “best-fit” map resulting from dispersion modelling obtained considering a SOER of 0.07 ouE m$^{-2}$ s$^{-1}$ constant with the wind speed.

Figure 19. Comparison between plume extent determined by IV field inspection (violet line) and “best-fit” map resulting from dispersion modelling obtained considering a SOER of 0.1 ouE m$^{-2}$ s$^{-1}$ constant with the wind speed.
Another interesting element for the comparison between field assessments and model outputs is the result of the dispersion model run referred to the VI measurement cycle, during which the assessors weren’t able to recognize the presence of odours coming from the landfill on the inspected paths. The map resulting from dispersion modelling obtained by considering a constant SOER of 0.25 ouE m\(^{-2}\) s\(^{-1}\) is shown in Figure 20. The pink line indicated in Figure 20 represents the internal perimetral street of the landfill, which is the closest path to the emission source that could be inspected by the assessors. It is clearly visible that in correspondence of this path, the modelled odour concentration is mostly below 1 ouE m\(^{-3}\); only in a small portion of the path the iso-concentration line corresponding to 2 ouE m\(^{-3}\), which is the lower limit of the odour recognition threshold, is crossed. If the previous considerations about the possibility that the SOER of 0.25 ouE m\(^{-2}\) s\(^{-1}\) might be overestimated, the failed odour perception by the assessors in the field appears justified by a particular situation in which the odour emissions from the landfill were hardly perceivable even at a low distance from the source, as proven by the model.

Figure 20. Map resulting from dispersion modelling relevant to the VI field measurement cycle obtained considering a constant SOER of 0.25 ouE m\(^{-2}\) s\(^{-1}\). The pink line indicates the internal perimetral street of the landfill.
4.2 Influence of the peak-to-mean factor

In order to perceive an odour, it is sufficient that its odour concentration exceeds the detection threshold for the duration of a breath (about 3.6 seconds). Odour concentration, as well as any other atmospheric scalar variable, is subject to instantaneous fluctuations due to turbulence. Given that the adopted model calculates the hourly mean odour concentration value, it is necessary to deduce the peak odour concentration, defined as the concentration that in one hour is exceeded with a probability of $10^{-3}$, i.e. for over 3.6 seconds. The peak odour concentration can be obtained by multiplying the hourly mean odour concentration by a coefficient called peak-to-mean factor (Schauberger et al., 2000; Capelli et al., 2011). Some recent scientific studies discuss the opportunity to consider a variable peak-to-mean factor, evaluated as a function of the distance from the source and the stability class (Schauberger et al., 2000; Schauburger et al., 2012). More in detail, some studies (Piringer et al., 2007) prove that, at close distance from the source (< 100 m), and with unstable atmospheric conditions, the peak-to-mean factor can reach values of 50, which then rapidly decreases with the distance as to reach a value of 1 at about 1000 m from the source.

Despite these experimental evidences, in this study, a constant peak-to-mean factor was adopted in accordance with the regional guidelines in matter of odour. It is important to highlight that, for all field measurement cycles, the presence of odour from the landfill was detected only in proximity of the source (significantly below 1000 m).

Therefore, all the above comparisons between model outputs and field inspections (Figure 8 - Figure 17) are conducted at very close distance from the source (few tenths/ hundreds of meters). In these conditions, the considerations about the dependence of the peak-to-mean factor from the distance from the source become significant. Based on the graphs shown in the paper by Piringer et al. (2007), it appears that at such distances higher peak-to-mean factors than the value of 2.3 suggested by the regional guideline should be used (probably in a range of 5-10).
If this hold true, then the “best fit” SOER values evaluated in order to maximize the correspondence between model outputs and field inspections as described in section 4.1 would result further reduced, probably approaching values in the order of 0.05 – 0.1 ouE m$^{-2}$ s$^{-1}$.

5. CONCLUSIONS

This study has the specific aim of evaluating the most suitable method to estimate odour emissions from a landfill surface, thereby counterposing two substantially different approaches: the one that treats the landfill as a fully passive area source, thereby considering the SOER as a function of the wind speed blowing over the surface, and the one that considers the odour emissions as independent from the wind speed over the landfill surface, in agreement with the most recent studies on the matter.

The comparison of the field assessments and the model outputs obtained by considering the landfill SOER as a function of the wind speed clearly highlights that this approach significantly overestimates the landfill odour emissions.

This overestimation is even more emphasized considering the discussion about the peak-to-mean factor reported in the previous section (4.2), which points out that the peak-to-mean factor adopted for the evaluation of the peak odour concentrations should be increased, presumably by a factor 2.

On the contrary, the comparison of the model simulations based on a constant SOER, independent from the wind speed results in a good correspondence between model outputs and field assessments, both in terms of shape and extension of the determined odour plume extents. Correspondence between simulated and experimentally assessed plume extents is optimized for constant SOER values comprised between 0.07 and 0.25 ouE m$^{-2}$ s$^{-1}$. As previously mentioned, considering that the peak-to-mean factor of 2.3 used for the simulations is likely to be underestimated, an even better fit would be expected for constant SOER values in the order of 0.05 – 0.1 ouE m$^{-2}$ s$^{-1}$.

In conclusion, this study proves that landfill surfaces cannot be considered as equivalent to fully passive area source, since the main driving force for volatilization of odours into the atmosphere is not forced
convection, as already discussed in previous recent research work on this subject. As a general rule, odour emissions from this particular kind of source should be considered as independent from the wind speed (i.e. constant). Moreover, the opportunity to use alternative methods instead of WT, which generally tend to overestimate emissions from low-emissive odour sources such as landfill surfaces, can also be considered for this purpose, as has been proposed in other works (Lucernoni et al., 2016c; 2017a).

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