IN-DEPTH ANALYSIS ON ODOUR DISPERSION MODELLING AND ITS APPLICATIONS TO WASTE MANAGEMENT OPERATIONS

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ABSTRACT
The management of waste entails the emission of a large variety of compounds into the atmosphere. Waste management processes (e.g. collection and transportation of waste, discharging of waste in dedicated facilities, mechanical–biological treatments and landfill disposal) are known for causing the problem of odour nuisance in the vicinity of waste treatment plants. Substances like volatile organic compounds, sulphides and nitrogen-based compounds are usually associated with waste management processes and, in general, are characterised by low odour threshold values, i.e. they are detected by the human sense of smell even at relatively low concentrations in ambient air. Dispersion modelling represents a fundamental step for the estimation of the odour impact near odour emission sources. However, the results of odour dispersion simulations are strongly affected by the initial hypotheses on the emission sources considered, by specific modelling parameters and by the quality of meteorological and morphological input data. In addition, the variability in the human perception of odour may not allow making universal conclusions on the results of an odour impact assessment, and this further complicates the matter. The aim of this paper is to shed light on the criticalities involved in the assessment of the odour impacts from waste management activities. The paper analyses and discusses the potential influences of the choices made during the preparation of dispersion modelling simulations. This contribution is expected to enrich the knowledge base on odour dispersion modelling and to help proponents, environmental consultants and environmental agencies to estimate the impacts induced by current and future waste management operations.
Keywords: odour nuisance, emissions, odour impact, waste treatments, mechanical–biological treatments, dispersion models.

1 INTRODUCTION

Several anthropogenic activities are known causes of environmental pressure, health impacts and nuisance to the settled population. In terms of local impacts, noise and air pollution including particulate matter, are the most evident types of environmental contamination to human beings, who can directly sense those forms of pollution through hearing, the sight and the sense of smell [1]–[6]. The latter allows for the "perception of smell", which is one of the most known definitions of odour [7]. Starting from the last century, several countries worldwide have adopted regulations to limit the ambient air concentrations of various air pollutants, especially macro-pollutants. However, many countries still do not have regulations to limit the impacts of odorants on people, except for prescriptions regarding the comparison of the results of modelling simulations with odour concentration limits during the authorisation procedure of specific activities [8]. Where odour regulations are available, prescriptions are highly variable both among countries and, in some cases, within the same country [9]. In addition, the characteristics of subjectivity of smell perception complicates the matter and differentiates the impacts experienced by the exposed population [10]–[12].

The exposure to malodorous compounds has detrimental effects on human well-being, which are mainly mediated by psychological effects [13]. The prolonged or repetitive exposure to odorants may cause nuisance. The latter, on its turn, may cause a wide variety of adverse effects on human beings, which can be classified as direct or indirect effects: direct

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effects may include psychological symptoms, like irritability, depression, mental confusion [14], and physiological symptoms like headache, sleepiness, nausea, respiratory and cardiovascular effects [15]–[17]; indirect effects derive from direct effects and may lead to negative socio-economic consequences in the geographical context where odour nuisance is experienced. For example, odour nuisance may cause complaints by the exposed population, which can cause the shut-down of the activities that are responsible for the emission of odorants in an area [18]. In tourist areas, odour nuisance may cause the decline of tourism, decrease the quality of life and, in general, odour nuisance may cause the loss of values of houses or terrains and influence the property market [19]–[22].

The problem of odours is related to the exposure to odorant compounds, i.e. substances whose ambient air concentrations exceed their respective odour thresholds in the proximity of target individual (receptor). The compounds characterised by the lowest odour thresholds are typically volatile organic compounds, sulphides, mercaptans, amines, chlorine compounds, indole and skatole [23]. The relationship between the odour concentration of a single compound and its mass concentration in ambient air is generally linear at high mass concentration values (> 1 ppm). However, at lower concentrations, the odour concentration of some pollutants shows a logarithmic trend [24]. This suggests that the overall odour concentration of a mixture may not be predicted by the mass concentrations of the single compounds in the mixture and the related odour threshold values.

While the exposure to odorants is usually associated with reversible symptoms, like those previously reported, the presence of specific compounds in the odorant mixture with adverse effects on humans may cause negative implications on health. Their effects depend on the type of exposure (short-term or long-term), the toxicological characteristics of each compound and the exposure concentration. Long-term exposure to relatively low concentrations should be considered a greater matter of concern if the exposure concentrations are lower than the odour thresholds of the toxic compounds inhaled. This may be the case of benzene, for instance, whose odour threshold determined by Yokio and Nagata [23] is 2.7 ppm. According to the inhalation unit risk provided by the U.S. Environmental Protection Agency [25], the exposure to benzene at a concentration that equals the benzene odour threshold would induce a cancer risk of 7.2×10^{-2}, which exceeds the acceptable cancer risk for exposure to single carcinogenic compounds (1×10^{-6}) by almost five orders of magnitude. In situations where highly toxic compounds are involved, the exposure to odorants may become a matter of human health.

Odour nuisance is caused by various human activities, but it has been especially related to waste management, wastewater treatments and zootechnical activities [10], [26]–[28], which are known sources of the odorant compounds mentioned above. There are many waste processes that cause the problem of odour nuisance, especially waste collection and transportation, waste discharge in dedicated facilities, mechanical–biological treatments (MBTs) of municipal solid waste and landfill disposal. When estimating the impact of odour emissions, the key question is how to properly model each specific emission source. However, there are other crucial choices that may influence the final results and lead to underestimate or overestimate the impacts of specific activities on the environment and the population, e.g. the choice of meteorological data, the meteorological stations, the computational domain and its resolution, the sensitive receptors, whether or not considering terrain elevation, etc.

The present paper moves from the considerations expressed above to discuss the potential influence of input data and modelling choices on the results of the application of modelling techniques for odour dispersion and impact assessment, with a specific focus on odour emissions from waste treatments. After an initial review of relevant publications on the topic of odour dispersion modelling from waste treatment activities, the paper will analyse and discuss the main results of the articles considered and provide indications that may turn useful for further applications of dispersion modelling techniques in this field. Such indications will consider the provisions included in the guidelines on odour impact assessment developed in many countries worldwide. The final aim is two-fold: (1) to help the proponents (and their consultants) of new waste management activities estimate the impacts induced by future waste management operations; and (2) to help the environmental agencies assess the projects according to the environmental impact assessment procedures.

2 GENERALITIES ON DISPERSION MODELLING AND EXAMPLES OF APPLICATIONS TO THE WASTE SECTOR

Odour impacts are normally assessed comparing the results of the application of dispersion models with criteria that depend on the regulations in force in a specific country/region. Dispersion models combine meteorological and morphological input data with the characteristics of the emission sources considered. By implementing equations that describe the mechanisms of convection and diffusion of gases and particles, dispersion models predict the ambient air concentration and the atmospheric deposition to soil of different air pollutants. In the last decades, the technology advances in terms of computational capability have made dispersion modelling affordable to end users at a large scale, simplifying and speeding up the assessment of new or existing activities, while keeping the accuracy of predictions at high levels. This has made dispersion modelling a key step in the environmental impact assessment process [8].

Different types of dispersion models exist, which can be classified into three main categories: gaussian plume, Lagrangian and Eulerian models. Gaussian plume models assume that the distribution of pollutants follows a normal probability distribution in the vertical and in the horizontal directions. They solve the Gaussian plume distribution equation and are particularly used to simulate the dispersion of continuous plumes of pollutants and (in the case of Gaussian puff models) discontinuous sources. Since Gaussian models solve only one equation, they are characterised by fast calculation time. As a drawback, such models must be used with caution when calm wind conditions are frequent and only diffusion occurs [29].

Lagrangian models consider the pollutant as particles that move following buoyancy, wind field and a random process simulating turbulence. Such models calculate the trajectories of a large number of particles by solving ordinary differential equations and use a reference system that follows the particles. Lagrangian models allow for fast calculation time especially in small-scale applications (tens of km), but the computational time increases significantly with the size of the domain and, thus, with the number of trajectories that must be calculated. Puff models area a particular case of Lagrangian and Gaussian models: they simulate the plume as a series of particle releases (puffs), which are treated initially with a Gaussian scheme and then move following a Lagrangian scheme.

Contrarily to Lagrangian models, Eulerian models consider a fixed reference system and the pollutant dispersion is calculated by solving the transport equation. Due to their high computational cost, they are generally used in mesoscale applications to simulate the long-range transport of pollutants and their chemistry [30]. Table 1 presents the most known and used dispersion models according to the approach followed for the computation of air pollutant dispersion.

Originally intended for the prediction of the impact of air pollutants, dispersion modelling have been lately used also to assess the potential impact of odour emissions, as demonstrated

Table 1: List of the most known atmospheric dispersion models used in air quality assessment applications.

Model name	Model type	Developer	License
AERMOD	Gaussian	U.S. Environmental Protection Agency	Open source
ADMS	Gaussian	Cambridge Environmental Research Consultants	Commercial
AUSTAL2000	Lagrangian	Ingenieurbüro Janicke	Open source
CALPUFF	Lagrangian	U.S. Environmental Protection Agency	Open source
CALINE3	Gaussian	U.S. Environmental Protection Agency	Open source
CMAQ	Eulerian	U.S. Environmental Protection Agency	Open source
GEOS-Chem	Eulerian	Harvard and Dalhousie Universities	Open source
HYSPLIT	Lagrangian	National Oceanic and Atmospheric Administration	Open source
ISC3	Gaussian	U.S. Environmental Protection Agency	Open source
WRF-Chem	Eulerian	National Center for Atmospheric Research	Open source

by the large number of publications available in the literature. However, concerning waste management, most papers deal with the wastewater sector. The interest in this sector is visible, for instance, by the recent introduction of the guidelines on odour impacts published by the Lombardy region (Italy), which dedicate a specific document on wastewater treatment plants and propose odour emission factors for specific wastewater treatments [31]. The literature on the application of dispersion models to solid waste treatments and related activities is limited to a small number of publications, mainly concerning the odour impacts of landfills and MBTs, with a minor number of publications on waste collection. In the following sections, recent available publications on odour dispersion modelling applied to waste management activities are reviewed, based on their respective field of application.

The waste management activities are known to contribute to possible odour impacts due to their continuous operation over time. This is the case, for instance, of municipal solid waste (MSW) landfills and MBTs. As a matter of fact, waste collection and transportation are occasional operations that may not affect residents continuatively. In addition, to the authors' knowledge, the application of dispersion modelling to this kind of activities is very limited and the literature lacks studies on this topic. An attempt to define the potential impact of waste transportation was made by Xu et al. [32] who, however, did not consider odour dispersion but only the dispersion of the only ethanol, considered as a representative odorous compound.

One of the problems in modelling landfills is related to the variations in shape and in the surface occupied by active landfills over the simulation period, which, in the case of odour impact and health risk assessments, is normally one year. Another matter of concern is the expected spatial and temporal variability of the odour emission rate, since this may vary depending on the type and age of waste. In their recent work, Szałata et al. [33] solved these issues by implementing a trial-and-error procedure with CALPUFF to estimate the specific odour emission rate (SOER) adopted in their case study, which resulted as 5.1 $ou_E/m^2/s$ (as a matter of fact, landfill sites are normally modelled as area sources). The trial-and-error procedure was based on odour sampling and following determination of the odour concentration of the sample by dynamic olfactometry (EN 13725:2003) in the vicinity of the landfill site. Dynamic olfactometry is a technique that considers a panel of selected examiners, who are subjected to increasing concentrations of the sample, which is diluted with fresh air by an olfactometer. The odour concentration (C_{od}) of the sample corresponds to the geometric mean of the number of dilutions that are necessary to each panellist to perceive the odour [34].

Alternatively, a more direct approach can be adopted [35]: a flux chamber and Nalophan® sampling bags can be used to take odour samples directly on representative portions of the landfill surface, according to the EN 13725:2003 standard. The samples can be analysed by dynamic olfactometry to determine the C_{od} of each sample, expressed as European odour units (ou_E) per m^3. Based on the inlet flow rate of the flux chamber (Q, m^3/s) and its sampling area (A_W, m^2), the SOER ($ou_E/m^2/s$) can be calculated as follows:

$$SOER = \frac{Q \cdot C_{od}}{A_W}. \tag{1}$$

In a recent work, Tagliaferri et al. [36] analyse how specific choices can affect the results of dispersion models applied to waste landfills. According to the authors, the most critical aspect is the characterisation of the emission sources, in terms of source geometry and odour emission rate (OER). Regarding source geometry, dispersion models require the definition of an initial vertical dispersion coefficient ($\sigma_{z,0}$, expressed as m), representing the initial vertical dimension of the plume. In the case of area sources (e.g., landfills), the choice of this value is particularly difficult: landfills are characterised by large surface areas, above which different degrees of turbulence may occur. In the work by Tagliaferri et al. [36], different choices of $\sigma_{z,0}$ generated odour concentrations at the receptor points that differed by a factor of three.

In a recent paper, Toledo et al. [37] evaluated the dispersion of odour from waste composting. The authors assume the plant as a point source with an OER calculated multiplying the SOER (obtained through odour sampling on the waste piles and following olfactometric analysis) by the emission area of waste piles. In another paper [38] on an anaerobic digestion plant for municipal solid waste, the following emission sources were identified: a heap of yard waste and a biofilter for air pollution and odour control. Both the sources were modelled as area sources; the biofilter was characterised by an output velocity of the treated effluent, while free convection was assumed for the yard waste heap. SOER were estimated by applying a flux chamber on the waste yard heap and on the biofilter surface. The authors compared the results of the application of CALPUFF on the anaerobic digestion plant with field measurements and found good agreement between the two solutions.

When present, biofilters are one of the main sources of odour in MBT plants. They are intended as a pollution control technology for polluted air streams that can be conveyed. For this reason, they have been largely employed in aerobic MBTs of waste, where large airflow rates are needed to stabilise the waste biomass.

Luciano et al. [39] applied CALPUFF to simulate the dispersion of odour from two biofilters to investigate the effects of the enlargement of an existing MBT plant. The authors derived the SOER through odour sampling and dynamic olfactometry in one case (EN 13725: 2003) and applying the local concentration limit value of 300 ou_E/m^3 on the biofilter surface in another case [31]. A different model (AERMOD) was used in a publication on municipal solid waste bio-drying [40]. In this publication, a conventional open-bed biofilter was compared with an array of bio-trickling filters to evaluate the potential improvements in the surroundings of a plant In terms of air quality and odour impact. The biofilter was simulated as an active area source, while the bio-trickling filters were simulated as point sources. Indeed, bio-trickling filters can convey the treated air stream and release it from a stack. The advantages of bio-trickling filters are noteworthy: the higher outlet velocity of the treated air released by bio-trickling filters guarantees a stronger dispersion of the pollutants and odorants in the atmosphere than biofilters, whose outlet velocity is about 200 times lower. The simulations revealed that a replacement of an open biofilter with an equivalent array of bio-trickling filters may reduce the impacts in the vicinity of the plant by > 90%.

3 DISCUSSION AND BEST PRACTICES FOR FUTURE APPLICATIONS

The experiences that are described in the papers presented in the previous section allow elaborating a discussion for future applications of dispersion modelling to waste-related activities. Part of the following advice is also included in the guidelines and regulations on odour impact assessment of various countries worldwide [9].

3.1 Computational domain

Defining a computational domain for a simulation means selecting its size, the horizontal and vertical resolution and the location of sensitive receptors. The extension of the domain should be chosen to include the areas where the highest impact is expected, and all the sensitive receptors identified. Depending on the model, the user can choose between a cartesian or a polar grid. However, some guidelines/regulations on odour impact make explicit reference to cartesian grids. As a rule, the horizontal grid cell size should be always lower than the minimum distance between the emission source(s) and the nearest sensitive receptor. Since odour impact is generally evaluated at a local scale, an adequate value of cell size should be comprised between 25 and 250 m [31], [41]. However, it is preferable to determine the horizontal cell size through a sensitivity analysis, reducing the cell size until the location of the areas with the highest impacts become independent of the cell size itself.

The definition of sensitive receptors allows for the calculation of statistics on the C_{od} expected in the selected points. This step is essential to verify the compliance with the regulations in force. Different guidelines/regulations provide instructions on the definition of receptor points: for instance, guidelines/regulations may specify the kinds of receptors (e.g., the nearest house, schools, hospitals), the minimum number and the distribution of receptors around the emission source(s) to be considered.

3.2 Meteorological data

Air dispersion models require the pre-processing of meteorological data to compute the wind field for every timestep. The nature of the meteorological data depends on the dispersion model chosen. Normally, dispersion models give two options: the possibility of using a wind field library generated by an external meteorological model (e.g., the weather research and forecasting model (WRF)) and the possibility of generating a wind field library with the model's meteorological pre-processor. The second option requires the availability of surface meteorological observations (recorded by meteorological or air quality stations) near the emission sources to be modelled.

Some guidelines/regulations on odour impact assessment set specific requirements on the maximum distance of meteorological stations from the nearest emission source and on the locations of the meteorological stations that can be considered as representative of the area. For instance, in Italy, regional guidelines require at least one meteorological station at a distance < 10 km from the nearest emission source. In the case of complex orography [41], [42], the meteorological station(s) must be located in the same valley of the emission sources [31], [43]. The same guidelines set minimum requirements on data quality (e.g., minimum anemometer elevation, minimum frequency of observations, minimum simulation period, maximum percentage of invalid data). In addition to surface observations, some dispersion models, like CALPUFF or AERMOD, require upper air soundings. In case the aforementioned requirements cannot be fulfilled, meteorological data should be retrieved by applying an external meteorological model.

3.3 Elevation data

Orography significantly affects the results of a dispersion model. The presence of terrain elevation is responsible for altering the wind field compared to a situation with flat terrain. According to the guidelines of the Lombardy region (Italy), for instance, terrain elevation should be taken into account if the ratio between the maximum difference in elevation within the computational domain and the size of the minimum horizontal dimension of the domain exceeds the value of 0.01 [31]. The Shuttle Radar Topography Mission (SRTM) of the U.S. Geological Survey (USGS) has made elevation data available for many countries worldwide [44]. The data are available for download upon registration.

The presence of buildings can also be taken into account in most of the dispersion models available. Like orography, buildings may affect the dispersion of air pollutants and odorants. The phenomenon of building downwash occurs when an emission source is located upwind of a building, whose height and/or width are sufficiently high to generate a turbulent flow downstream that can bring the plume to the ground and increase the impacts at ground level [45]. To account for this phenomenon, many available dispersion models contain a module for building downwash calculation that requires the explicit definition of the buildings near the emission source. However, the presence of buildings may also affect areas that are far from the emission sources, since it modifies the surface roughness of the ground. For this reason, many dispersion models allow defining the spatial distribution of surface roughness in an explicit way or requiring land use maps as input files. Peculiar situations (e.g., emission of air pollutants or odour in urban areas) may require the explicit definition of buildings for a proper evaluation of the population exposure. This is particularly useful when assessing the impacts of transportation in canyon-like streets [46]. Among the most known dispersion models, AUSTAL2000 allows the user to create and import a raster map of building elevations to explicitly define buildings within a portion of the computational domain.

3.4 Emission characterisation

The complete characterisation of emission sources is generally challenging and is usually affected by high uncertainties, especially in the case of diffusive sources. The definition of conveyed sources is an easier task: for this kind of sources, OER values can be measured by odour sampling at the source and dynamic olfactometry; alternatively, odour emission factors (or C_{od} values to be multiplied by the airflow rate) can be retrieved in the literature or in previous odour impact assessment studies, if similar cases have been studied. However, if the purpose is to assess the maximum permissible impacts within the computational domain, the user should consider the OER limit values in force in the country/region. On the contrary, diffusive or passive sources are normally unpredictable and, in order to obtain the best results, the definition of OER (or SOER for area sources) values requires the measurement of odour concentrations.

In the case of waste landfills, due to the expected spatial and temporal variability of the odour emission rate from the landfill surface, olfactometric analyses play a fundamental role in the definition of a representative SOER. The latter could be determined directly by sampling the landfill surface via wind tunnels or flux chambers. According to Lucernoni et al. [47], flux chambers are preferable, due to the tendency of wind tunnels to overestimate the emission rate. The final SOER value could be defined as the geometrical mean of the SOER values measured in different points of the landfill surface [36]. If the landfill surface is not accessible, the SOER can be determined indirectly, by following the procedure adopted by Szałata et al. [33]: assuming tentative values of SOER in the model and selecting the value that allows the model results to match the results of the olfactometric analyses carried out in the vicinity of the landfill site.

Model validation, performed by on-field sampling and dynamic olfactometry, plays a key role in the choice of the best parameters that characterise the emission source, including $\sigma_{z,0}$ [36]. Brancher et al. [48] stress the importance of considering hourly-resolved OER values when evaluating low percentiles of odour concentration at receptor points. By implementing a stochastic approach based on a Monte Carlo method, the authors proved this choice to deliver more robust results. However, when high-end percentiles are the terms of reference of odour impact criteria, assuming a constant OER is preferable, since the effort to generate hourly-resolved OER values is not adequately paid back by the quality of the results.

Besides diffusive sources that can be logically modelled as area sources (e.g., landfills or waste heaps in open air), there are other sources that require particular attention and, possibly, a different approach. This is the case, for instance, of warehouses or buildings containing waste, with permanent lateral openings or, alternatively, portals that are normally kept closed, but that can be opened during the operation of a waste treatment facility. Inside these buildings, odorants are released by the waste that is stored or moved by machineries. Such buildings become emission sources when the portals are opened or if lateral openings are present. The characterisation of such sources is challenging and the literature lacks publications on this topic. According to the user's guides of the most known dispersion models, this kind of sources could be modelled as volumetric sources, i.e. sources for which it is possible to define both initial vertical ($\sigma_{z,0}$) and horizontal ($\sigma_{y,0}$) dispersion coefficients. In the case of odour emissions from a building, useful indications on how to define volumetric sources are provided by the Ministry for the Environment of New Zealand [49]: as a first approximation, $\sigma_{z,0}$ and $\sigma_{y,0}$ can be assumed respectively as the building height and the building minimum lateral dimension, both multiplied by 0.25.

The definition of the OER is also a critical point when dealing with volumetric sources. Contrarily to point or area sources, for which OER may be obtained by similar cases in the literature or by odour sampling and dynamic olfactometry, situations that may be modelled as volumetric sources are less common and difficult to generalise. However, in many practical odour impact assessment procedures, the problem of the definition of the OER is usually treated as follows:

- Firstly, it is necessary to retrieve a representative C_{od} value in the indoor environment. Odour sampling and dynamic olfactometry, though more time consuming and expensive, are expected to deliver the best estimation. Alternatively, this can be done by retrieving C_{od} values related to the same kind of waste in the literature or in similar case studies.
- Secondly, it is necessary to estimate the air exchange rate between indoors and outdoors. This this step is particularly affected by uncertainties. An empirical approach consists of considering the number of times the building door is opened during the day, the vertical area of the building opening, the mean wind speed at the nearest anemometer or grid point where meteorological data were calculated by the meteorological pre-processor. This way it is possible to estimate the volumetric airflow rate through the opening, which can be assumed as equal to the volumetric airflow rate of the air exiting the building. As

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a precautionary measure, in a first approximation, the wind direction might be assumed as perpendicular to the building opening.

- Finally, the OER (ouE/s) can be estimated multiplying C_{od} by the volumetric airflow rate calculated at the previous step. Volume sources may be used also to simulate the movement of vehicles if the dispersion model does not allow defining line sources. In this case, it is suggested to define a series of multiple volumetric sources separated by < 0.25 times the distance to the nearest receptor point.

4 CONCLUSIONS

The present paper discussed the role of dispersion modelling for odour impact assessment applied to waste management activities. The paper highlighted some critical issues in the application of dispersion models. Despite the advances achieved over the last decades in terms of programming and computational capability, modelling the phenomena of odour emission, dispersion and perception by humans is still challenging and is affected by a high degree of uncertainty. This is due in part to the subjectivity of human perception and in part to the chemical composition of odour emissions. The latter may change along the path of the plume. In addition, the odour concentration of some compounds was found not to increase linearly with their mass concentration in air. There is also a great uncertainty in the characterisation of emission sources, especially diffusive sources that are normally treated as passive area and volumetric sources. The measurement of odour concentration and OER by sampling and dynamic olfactometry still plays a key role in the validation of model results and should not be replaced entirely by dispersion modelling, except for the case when the same dispersion model is applied more times to the same site where it was previously validated. Although the suggestions and recommendations here discussed are proposed for application to waste management activities and odour impact assessment, they may be equally applied to any other field and pollutants.

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