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Are Empirical Equations an Appropriate Tool to Assess Separation Distances to Avoid Odour Annoyance?

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Received: 29 April 2020; Accepted: 24 June 2020; Published: 27 June 2020

Abstract: Annoyance due to environmental odour exposure is in many jurisdictions evaluated by a yes/no decision. Such a binary decision has been typically achieved via odour impact criteria (OIC) and, when applicable, the resultant separation distances between emission sources and residential areas. If the receptors lie inside the required separation distance, odour exposure is characterised with the potential of causing excessive annoyance. The state-of-the-art methodology to determine separation distances is based on two general steps: (i) calculation of the odour exposure (time series of ambient odour concentrations) using dispersion models and (ii) determination of separation distances through the evaluation of this odour exposure by OIC. Regarding meteorological input data, dispersion models need standard meteorological observations and/or atmospheric stability typically on an hourly basis, which requires expertise in this field. In the planning phase, and as a screening tool, an educated guess of the necessary separation distances to avoid annoyance is in some cases sufficient. Therefore, empirical equations (EQs) are in use to substitute the more time-consuming and costly application of dispersion models. Because the separation distance shape often resembles the wind distribution of a site, wind data should be included in such approaches. Otherwise, the resultant separation distance shape is simply given by a circle around the emission source. Here, an outline of selected empirical equations is given, and it is shown that only a few of them properly reflect the meteorological situation of a site. Furthermore, for three case studies, separation distances as calculated from empirical equations were compared against those from Gaussian plume and Lagrangian particle dispersion models. Overall, our results suggest that some empirical equations reach their limitation in the sense that they are not successful in capturing the inherent complexity of dispersion models. However, empirical equations, developed for Germany and Austria, have the potential to deliver reasonable results, especially if used within the conditions for which they were designed. The main advantage of empirical equations lies in the simplification of the meteorological input data and their use in a fast and straightforward approach.

Keywords: environmental odour; emission; annoyance; separation distance; dispersion models; empirical equations

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1. Introduction

Odours from industrial, municipal, and agricultural activities are the most common causes of public complaints to authorities, besides noise. Effectively tackling such complaints is an essential part of environmental odour management practices. Separation distances between odour-emitting facilities and residential areas can be imposed to restrict annoyance within acceptable levels. Doing so has the potential to prevent complaints from being generated in the first place. These separation distances divide the circumjacent area around a source into a zone which is protected from annoyance and a zone closer than the separation distance where annoyance is likely to be expected. The term setback distance has also been commonly used in this context.

Governments around the world have set jurisdictional limit values for environmental odours, called odour impact criteria (OIC), to orientate compliance demonstration procedures. By this means, separation distances can be calculated on a case-by-case basis and in a direction-dependent manner. Dispersion modelling is a method extensively used for such a purpose. A variety of dispersion models are in use, differing mainly by their mathematical formulation to the physics driving the transport and dispersion of pollutants in the atmosphere. Currently, the most frequently used dispersion models are based on the Gaussian, Lagrangian, and Eulerian descriptions [1–7].

Estimates of downwind ambient concentrations of air pollutants, including odours, can be computed using the emission of the source, geophysical and meteorological data as the primary inputs. Even for cases in which the source emission is constant over time, the ambient concentrations will vary according to the meteorological conditions at the time of the release. Accordingly, meteorology is widely acknowledged as the principal factor in this context. Today's advanced dispersion models can also treat building downwash or buoyancy effects, which is not possible when applying empirical equations (EQs). The importance of acquiring good quality meteorological input data that is representative of the site being modelled is palpable as it is the meteorological expertise needed to obtain consistent results from dispersion models. Meteorological parameters such as wind direction and velocity, a measure of the degree of turbulence (atmospheric stability) and mixing height, typically on an hourly basis, form the basis of such datasets.

Hourly time series of ambient odour concentrations predicted by dispersion models are used to quantify odour exposure. The evaluation of the odour exposure is performed by OIC, commonly relying on a protection level. The level of protection is differentiated, for instance, by the zoning/land use of the area and facility status (new or existing installations). A review of OIC in 28 countries has been presented elsewhere [8]. Due to the application of such jurisdictional OIC, the annoyance potential of odours at a particular site can be assessed by direction-dependent separation distances [9–11].

The OIC are defined by an odour concentration threshold C_T, the exceedance probability P of this threshold (or percentile $1 - P$) and the model averaging time. There are basically two alternatives to calculate direction-dependent separation distances by OIC. The first alternative uses a constant C_T so that the protection level is adopted by P. This tactic has been defined in the German national guideline [12], which is from time to time adopted for compliance demonstrations in Austria and Switzerland too. The second alternative, which is established in the majority of the countries [8,13], works the other way round. First, P is set, then C_T is used to cover the targeted protection levels.

Odour-related separation distances do not apply to all kinds of sources. This approach is more appropriate for ground-level or low-height sources. These sources are typical of, for example, wastewater treatment plants and concentrated animal feeding operations. It is difficult to define the two zones given by separation distances for relatively high point sources unaffected by adjacent structures. The separation distance approach is part of an integrated multi-tool strategy to manage environmental odours [8].

Simplified tools have also been developed to enable a simpler determination of odour-related separation distances. Such tools are often called empirical equations (EQs). In this paper, we present and discuss various EQs used in some jurisdictions. These EQs were in some cases incorporated in regulations or national guidelines. Although a number of EQs are listed (see next section, Table 1), they do not represent an exhaustive review of available EQs, or even just those that use meteorological data as predictors. However, some background context is provided regarding the subset of EQs that do include meteorological predictors. These EQs have been well described individually in the published literature. However, little work has been done comparing the performance of EQs that include meteorology as a predictor with each other and dispersion modelling calculations. This has been done to demonstrate the advantages and shortcomings of such parsimonious methods.

2. Selected Empirical Equations to Assess the Separation Distance

There is a wide spectrum of empirical methods to assess separation distances. The presented EQs fill the gap between dispersion models, which are the gold standard and benchmark and guesswork on the other side. Simple EQs deliver a unique, fixed distance, thereby shaping a circle around the source. Consequently, this procedure does not take into account the meteorological conditions of a site. More elaborate EQs include meteorological predictors such as wind frequencies and mean wind velocities within direction sectors. In these cases, the EQ coefficients have been derived from regression analyses of dispersion model calculations.

Table 1 presents selected international EQs and their main input factors. This list is given with the intention of facilitating the calculation of separation distances in future works. The EQs are sorted descending by the complexity of the input parameters and the shape of the separation distance.

- Ideally, the following objectives should be fulfilled by EQs [5]:
- Odour emission rate: it should be quantified in the same way as it is done for dispersion models, using the odour emission rate (ou_E s^{-1}) even if the emission geometry cannot be taken into account;
- Odour impact criteria: the separation distance is calculated in reference to a certain protection level via the same odour impact criterion which are used for dispersion models;
- Meteorology: the meteorological situation of the site should be defined by wind statistics. These refer to at least the relative frequency of the wind direction for 10° sectors. Such meteorological datasets are accessible, for example, from national weather services;
- "Paper and pencil": the method should be fast and easy to use to be appropriate as a screening tool.

The first two EQs in Table 1 are the German VDI (Verein Deutscher Ingenieure) equation [5,14] and the Austrian equation [15]. The German VDI EQ uses only one meteorological predictor (wind direction frequency), whereas the Austrian EQ uses, in addition, the mean wind velocity for wind direction sectors of 10°. The mean wind velocity was added as a predictor with the objective of considering atmospheric stability, pragmatically. The reason this was considered is centred on the greater variability in atmospheric stability conditions and higher calm frequencies of Austrian sites as compared to most German sites.

Both EQs are based on a power function $E = a\,S^b$. Such a power function calculates the separation distance E (m) as a function of the odour source strength, given as the odour emission rate S (ou_E s^{-1}).

In Germany, the two coefficients a and b of the power function were fitted to dispersion model results obtained with AUSTAL2000, a Lagrangian particle dispersion model. The coefficient a depends on two predictors. The first is the relative frequency of the wind direction sectors F (‰) of 10°. The second is the odour exceedance probability P (%) of the odour impact criterion. The exponent b depends on P only. The exceedance probability is set depending on the required protection level. The equation for the separation distance E_G by the German VDI regression model reads

$$E_G = [(-0.0137\,P + 0.689) \times F + 0.251\,P + 0.0590]\,S^{\frac{1}{1.79+0.204\,P}} \quad (1)$$

Table 1. List of selected empirical equations (EQs) for the determination of the separation distance E used in different countries with indication to the predictors (independent variables) of the power function $E = a\ S^b$ with the factor a, the exponent b and the odour emission rate S. The protection level is related to odour impact criteria (OIC) (C_T concentration threshold in $\mathrm{ou_E\ m^{-3}}$ and P exceedance probability in %).

Name and Reference	**Factor a**	**Emission S**	**Exponent b**	**OIC C_T/p_T**	**Separation Distance Shape**
German VDI [1,2] [5,14]	wind frequency, exceedance probability	odour emission rate ($\mathrm{ou_E\ s^{-1}}$)	exceedance probability	0.25 $\mathrm{ou_E\ m^{-3}}$ / 7–40%	Shape corresponding to the wind frequency of 10° sectors
Austria [1,2] [15]	wind frequency, wind velocity, exceedance probability	odour emission rate ($\mathrm{ou_E\ s^{-1}}$)	wind frequency, exceedance probability	0.25 $\mathrm{ou_E\ m^{-3}}$ / 3–24%	Shape corresponding to the wind frequency of 10° sectors
Belgium [2] [16]	surface roughness, protection level (zoning)	number of animals, species, ventilation system, manure, feeding	$b = 0.5$	10 $\mathrm{ou_E\ m^{-3}}$ / 2%	Ellipse by 1.2 E and 0.8 E, orientated in the prevailing wind direction
Old Austrian guideline [17,18]	wind frequency, zoning	number of animals, species, technical factor (ventilation system, manure and feeding)	$b = 0.5$	–	Shape parametrised by the frequency of the wind direction for 45° sectors (factor between 0.6 and 1.0)
Purdue setback model [2] [19]	wind frequency, zoning, topography, orientation and shape of the building	odour emission rate ($\mathrm{ou_E\ s^{-1}}$)	$b = 0.5$	–	Shape parametrised by the frequency of the wind direction for 45° sectors (factor between 0.75 and 1.0)
Ontario M (cf. Guo, et al. [20])	$a = 1$	species, number of animals, zoning, manure	$b = 1$	–	Circle
W-T [1,2] [21]	$a = 1.60$	odour emission rate ($\mathrm{ou_E\ s^{-1}}$)	$b = 0.6$	–	Circle

[1] Compared against dispersion models. [2] Used for an intercomparison of empirical equations.

For example, for an odour emission rate S = 14,000 $\mathrm{ou_E\ s^{-1}}$ (which can correspond to about 1860 fattening pigs [22]), wind frequency F = 20‰ for a 10° sector and odour exceedance probabilities for residential areas (P = 10%) and rural areas (P = 15%), the separation distance E_G (m) returns 207 m and 152 m, respectively.

A minimum distance of 50 m was used for the regression coefficients estimation. It is thus recommended to reset to 50 m separation distances smaller than this minimum.

The German VDI EQ has been derived from dispersion model calculations at 23 sites. The German regulatory Lagrangian particle dispersion model (AUSTAL2000) was used. The exponent b and the multiplicative factor a of the power function ($E_G = a\ S^b$) have been obtained by three input parameters which were restricted in the range of an improved fit [5]. The basis of the power function is the odour emission rate S ($\mathrm{ou_E\ s^{-1}}$) in the range between $500 \leq S \leq 50{,}000$ $\mathrm{ou_E\ s^{-1}}$. The two other predictors are the frequency of the wind direction F (‰) of a 10° sector ($10 \leq F \leq 60$‰) and the odour exceedance probability P (%) ($7 \leq P \leq 40$%) of the odour impact criterion [12]. A single-point source with vertical release at a height of 5 m was considered for running the dispersion model. To apply the German VDI EQ also for wide-stretched odour sources (e.g., area sources), a focal point must be calculated by using the coordinates of individual odour sources, which are weighted by individual odour emission rates. An additional distance, depending on the extension of the wide-stretched source, will be added to the baseline separation distances calculated from the EQ [14]. Due to this determination, the requirement for a conservative approach was satisfied. To reduce the influence of the livestock building on the dispersion, the lowest calculable separation distance was set to 50 m. A guidance for the application of the German VDI EQ can be found in [23] discussing how the elongation of an odour source can be taken into account, how the wind statistics can be adapted for sites that are influenced by a valley wind system, how the hedonic tone of the species can be taken into account, how abatement measures to reduce odour emission can be considered, and case studies.

For the Austrian EQ, the regression analysis was done on the basis of dispersion calculations. The power function $E = a\ S^b$ is defined by the factor a and the exponent b, both of which depend on two meteorological parameters (the relative frequency of the wind direction F and the mean wind velocity W of the wind direction for 10° sectors), as well as P. The equation for the separation distance E_A by the Austrian regression model reads

$$E_A = P^{-0.389}\Big(165\,F^{0.0289} - 3.63\,W - 150\Big)\,S^{\frac{1}{-0.0381\,F+0.0191\,P+2.31}} \tag{2}$$

For the same inputs as in the example given above, but now considering a mean wind velocity of W = 2.5 $\mathrm{m\ s^{-1}}$ for a 10° sector, the separation distance E_A (m) returns 165 m and 97 m, respectively.

A minimum distance of 100 m was used for the regression coefficients estimation. This means that separation distances which are smaller than this minimum have to be reset to 100 m.

The Austrian EQ [15] has been derived based on dispersion model calculation at 6 sites. The model used was the Austrian Odour Dispersion Model (AODM) [2,24,25], a Gaussian plume dispersion model with a calculation scheme for the peak-to-mean factor, which depends on the travel distance and the stability of the atmosphere [26]. The exponent b and the multiplicative factor a of the power function ($E_A = a\ S^b$) are determined by four input parameters, which were also restricted in the range for an improved fit. The odour emission rate S ($\mathrm{ou_E\ s^{-1}}$) lies in the range between $400 \leq S \leq 24{,}000$ $\mathrm{ou_E\ s^{-1}}$. The two meteorological predictors for 10° sectors are the relative frequency of the wind direction $F \leq 160$‰ and the mean wind velocity $W < 4$ $\mathrm{m\ s^{-1}}$. The odour exceedance probability P (%) lies in the range of $3 \leq P \leq 24$%. The source geometry was a single-point source with a height of 6 m. The lowest calculable separation distance was set to 100 m, according to the limitations of the Gaussian dispersion model. The main difference between the two referred EQs is the best-fit approach for the Austrian equation, in contrast to a worst-case calculation for Germany.

The two EQs quantify the odour emission rate S ($\mathrm{ou_E\ s^{-1}}$) in the same way as it has to be done for dispersion modelling studies in their respective jurisdictions. This is a major advantage because the discrepancy between the results of the EQs and dispersion models is then related to effects other than the odour emission rate. Based on the simplification, the geometry of the emission cannot be included in the calculation by the EQs. The inclusion of such predictors is reserved to dispersion models. While the exponent b of the power function depends on the wind direction frequency and/or the odour exceedance probability in these equations, this parameter has a constant value for all other EQs in the range between 0.5 and 1.0.

The separation distance E_P of the Purdue EQ [19] reads as

$$E_P = a_P\, S^{0.5} \tag{3}$$

with the factor $a_P = 6.19\ F\ L\ T\ V$, which includes the impact of the wind frequency for 45° sector F, in the range of $0.75 < F < 1.0$, the land use factor L, describing the protection level for agricultural areas and pure residential areas between $0.5 < L < 1.0$, the topography T, describing good ventilated areas (flat terrain) and narrow valleys between $0.8 < L < 1.0$, and the orientation and the shape factor, describing the length to width (L/W) ratio of the livestock building V in relation to the wind direction in the range between $1.0 < V < 1.15$. The source strength S is given by the product of the specific odour emission factor per animal place ($\mathrm{ou_E\ s^{-1}}$) and the number of animals. Calculations are supported by a spread sheet [27].

The Williams and Thompson model (W-T) [21] is a worst-case approach giving the distance $E_{W\text{-}T}$ from the source, within which complaints are likely, to the odour emission rate S ($\mathrm{ou_E\ s^{-1}}$).

$$E_{W-T} = 1.60\, S^{0.6} \tag{4}$$

The other three EQs (Belgium [16], Old Austrian [17,18], and the Ontario (cf. Guo, Jacobson, Schmidt, Nicolai and Janni [20])) were not included in the comparison, because the odour emission rate S is parametrised by several empirical factors, which exclude an intuitive comparison with the other EQs.

A previous work [20] compared four EQs, Ontario (cf. [20]), the Williams and Thompson (W-T) [21], the old Austrian [18] and Purdue [19] EQs, against the Minnesota OFFSET model [28,29]. The last EQ does not deliver a pure separation distance. For several stability classes, wind velocities and protection levels (related to OIC), the factor a and the exponent b are given. In [20], the Minnesota OFFSET model was used as a reference for the other four EQs. All these EQs are based on a power function. The Purdue EQ [19] was a further development of the old Austrian EQ [18], with the advantage that the odour source S is given as odour rate and not parametrised by several empirical factors as it was previously suggested by the old Austrian EQ.

For some geographical areas, local environmental agencies have recommended locally adapted dispersion-based tools in combination with meteorological data for calculating separation distances. This simplifies the application of such tools because no specific meteorological knowledge is compulsory to run them.

For example, the German province North Rhine-Westphalia has developed a model called Screening Model for Odour Dispersion (SMOD) for planning and informative purposes of licensing procedures [30,31]. In The Netherlands, the V-Stacks model was developed for the entire area of the country [32]. For the Canadian province Manitoba, look-up tables have recently been developed based on AERMOD simulations [33]. Due to the fact that the meteorological data are an integral part of locally adapted solutions, these models cannot be transferred directly to other regions.

An EQ primarily developed for use in Switzerland [34] was not included in the intercomparison (Table 1) due to several reasons: (i) the odour emission rate is quantified by the odour intensity, (ii) the dilution is quantified by an exponential function, (iii) the description of the input parameters is incomplete, which means that a comparison with other EQs is not straightforward. Because no meteorological predictors are included for the calculations with the Swiss model, the separation distance is represented by a circle around the source. Similarly, an EQ derived with a view to assessing broiler farms in Western Australia [35] was not included as it did not to reach the point of having policy status.

Figure 1 depicts the separation distances calculated by using five EQs for a livestock building with 3000 fattening pigs (22,500 ou_E s^{-1}, [14]) for the meteorological situation for Wels, an Austrian site. The prevailing wind directions at this site were from WSW and ENE. The comparison shows the impact of the meteorological situation (exposed by the wind rose) on the separation distances, calculated by the EQs. The five EQs were selected from Table 1, the German and the Austrian EQs, which include the wind statistics of the site, the Belgian EQ with a rough parametrisation for the prevailing wind direction, the Purdue EQ, which uses the wind frequency of 45° sectors and the W-T EQ which does not consider the wind frequency as a predictor. For Easterly winds, the impact of the width of the wind sectors can be seen in comparison to the German and Austrian EQs with 10° sectors and the Purdue EQ with 45° sectors. The impact of the wind frequency is very similar for the Belgium and the Purdue EQs. The Belgian EQ shows only a weak influence of directional wind frequencies and forms an ellipse orientated towards the prevailing wind directions with 20% longer major axes. However, the wind frequency is not taken into account in detail. The range for the wind frequency factor F of the Purdue EQ is $0.75 < F < 1.0$, which results in a maximum of 33% greater separation distance in the prevailing wind direction, compared to 20% for the Belgian EQ. The German VDI and the Austrian EQs show the highest sensitivity to the wind frequency. The W-T EQ shows that a circle with a constant separation distance for all directions is unsuitable to describe the meteorological situation of the dilution process in the atmosphere. Even if the claim of this EQ is a worst-case assessment, the enormous overestimation of separation distances for several directions will not help in some cases to find an appropriate location for an odour source concerning the wind situation of the site and residential areas.

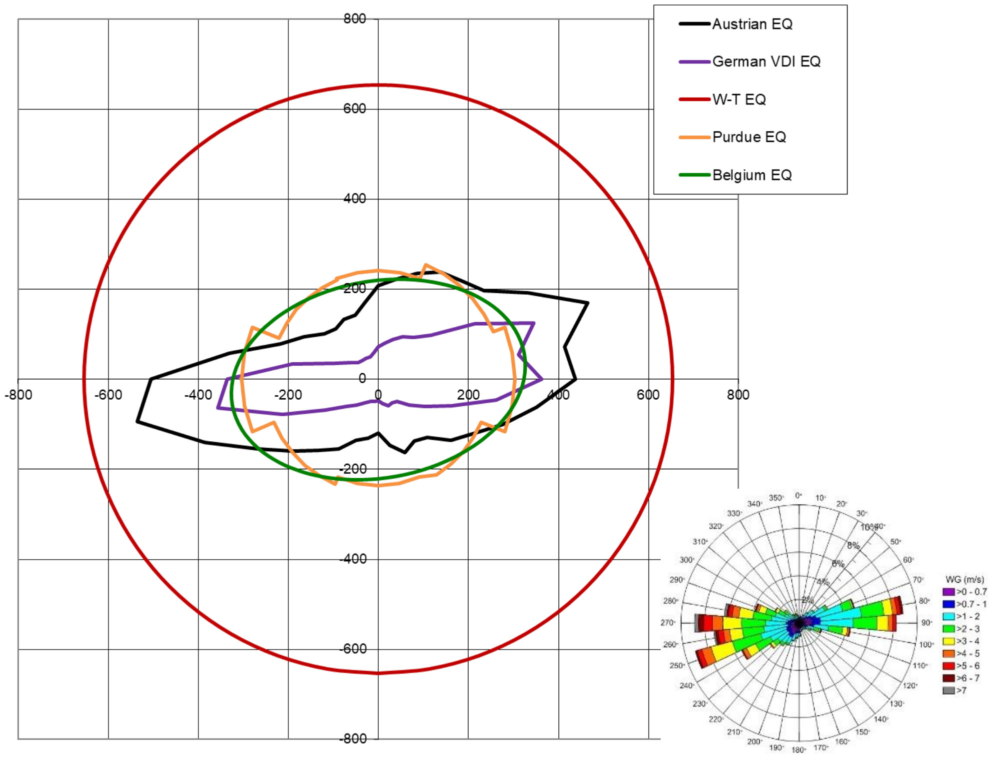

Figure 1. Separation distances calculated using the German VDI [5,14], Austrian [15], Belgian [16], Purdue [19] and Williams and Thompson (W-T) [21] empirical equations (EQs) for a protection level of rural areas and a 3000 head fattening pig livestock building. The wind statistics (frequency of wind directions and wind velocity per 10° sectors) from a site in Wels, Austria, are shown separately.

3. Case Studies

In this section, separation distances due to three selected EQs are qualitatively compared to those obtained from dispersion models. This is undertaken to explore the advantages and shortcomings of EQs. Moreover, the potential of EQs to be used as easy-to-use screening tools is tested. This comparison is carried out using available model data sets and thus is non-systematic. It is not intended to compare the output of the different dispersion models but the differences in separation distances between EQs and models. The following EQs have been selected: the two EQs from Germany and Austria, which include the wind statistics per 10° wind sectors, and the W-T EQ, which delivers a circle.

Dispersion models used for the comparison are AODM (used in the derivation of the Austrian EQ), LASAT (similar to AUSTAL2000, which was used to derive the German EQ) and the U.S. regulatory air quality model AERMOD. The latter has no link to any of the three EQs used for the comparison. Both an empirical-based peak-to-mean (p2m) procedure and a constant factor of 4 (f4) to account for short-term concentrations are considered for LASAT and AODM, as these models have in-house implementations of both schemes. As the p2m scheme could not promptly be incorporated for AERMOD, consequently, only the f4 scheme was used. The selected sites are located in Brazil, China, and Austria. Throughout the comparison, an odour impact criterion currently enforced in Germany [12] is applied. The German criterion is defined by an ambient concentration of 1 $ou_E\ m^{-3}$ as a short-term value. The constant factor of 4, f4, is in use to account for the human perception of odours, which translates into an hourly mean of $C_T = 0.25\ ou_E\ m^{-3}$.

3.1. São José dos Pinhais, Brazil

The Brazilian site (25.555° S, 49.132° W) is located in São José dos Pinhais, a city relatively close to Curitiba, the capital of the state of Paraná. This site lies in a plateau (known as "Planalto de Curitiba") shaped by gently rolling terrain. Different land uses can be found scattered around the site. The AERMOD Modelling System was used for the present investigation [36,37]. The extent to which AERMOD is suitable for assessing source impacts in this site has been shown in a previous study [38]. AERMOD is acknowledged as an advanced steady-state Gaussian plume model. It incorporates boundary layer turbulence theory and scaling concepts. The modelling system consists of three core modules: (i) the AERMOD dispersion model itself, (ii) the AERMET meteorological processor, and (iii) the AERMAP terrain processor. Versions 18,081 of these modules were used.

Here, a single-point source was selected for the prediction of ambient odour concentrations. The odour emission rate was $S = 15{,}000\ ou_E\ s^{-1}$. The source geometry was assumed circular, with a height of 10 m from the ground, a diameter of 1.0 m, and vertical release. The effluent was released with an exit velocity and temperature of 3.0 $m\ s^{-1}$ and 20 °C, respectively. A total of 2736 receptors were placed on a polar grid with a minimum distance from the source of 50 m. The receptors were set at breathing height (1.5 m). A digital elevation model was built using AERMAP on the basis of terrain data in SRTM1 (resolution of ~30 m). Elevations from near 880–918 m above sea level were observed within the model domain. The elevated terrain option was selected to consider that terrain heights can be above or below the stack base elevation.

Surface and upper air meteorological observations for 2015 were used as input data to AERMOD. The surface dataset, given by hourly values of air temperature, atmospheric pressure, cloud cover, wind direction and velocity, was obtained from the NOAA Integrated Surface Database [39] for Afonso Pena International Airport (25.531° S, 49.167° W, ~4.5 km from the site). The frequency of calm winds (<0.5 $m\ s^{-1}$) amounted to ~3.4% during 2015. Calms were not disregarded but reset to 0.5 $m\ s^{-1}$. Upper air soundings were obtained from the NOAA/ESRL Radiosonde Database [40] for the same airport and used as collected. The surface and upper air meteorological datasets were processed using AERMET, which in turn estimates the required boundary layer parameters for use by AERMOD. The Brazilian site has wind directions (at 10 m height) primarily from east to southeast (E–SE) together with secondary maxima from northeast to east-northeast (NE–ENE). The annual mean wind velocity was ~3.0 $m\ s^{-1}$. High velocities were observed from almost all quadrants, with a maximum of 19.0 $m\ s^{-1}$ for the period.

Finally, separation distances were calculated using AERMOD and the two previously described EQs. The tolerated exceedance probability of the concentration threshold was exemplarily taken to be P = 10%.

3.2. Beijing, People's Republic of China

The Chinese site (40.10° N, 116.16° E) is located ~30 km northwest from central Beijing. The city, with an average elevation of 43.5 m, is located at the northern part of the North China Plain. Beijing is enclosed by the Yanshan Mountains (average elevation 600–1500 m) to the north and the Taihang Mountains (average elevation 1500–2000 m) to the west [41]. Beijing is characterised by a monsoon-influenced, temperate continental climate, with humid and hot summers and dry, cold, and windy winters [42].

Odour emissions are due to a 300-head commercial dairy farm [43]. The terrain near the site is mostly flat, typically farmland. The farm has 0.67 km^2 of area, including feedlot pens, a feed mill, a slurry treatment workshop, and administrative offices. The farm contains three feedlot pens with a total area of 42,000 m^2 for raising the cows. The identified and quantified odour sources in the dairy farm include three barns for 100 cows each and the feed storage of corn silage.

Here, the results obtained in our previous work [43] are considered to augment the comparative analysis with the other two sites. Details on the use of the EQs, the AERMOD modelling approach and quantification of odour emissions at the Chinese site can be found in the referred previous work [43]. For convenience, a summary is presented below.

AERMOD, AERMET and AERMAP (versions 18081) were applied. The three barns were treated as area sources, for which a release height of 0.05 m was assumed. The feed storage was treated as a stack (release height of 2.5 m, exit velocity of 0.5 m s^{-1}, exit temperature of 20 °C and diameter of 0.8 m). The total odour emission rate of the dairy farm was S = 5850 ou_E s^{-1}. This value was attained based on emission factors given in the VDI 3894 Part 2 [14]. A polar receptor network with a minimum distance from the source of 50 m was defined, totalling 1656 receptors set at breathing height (1.5 m). A digital elevation model was created using AERMAP with terrain data in SRTM1. Elevations from near 40–55 m above sea level occurred within the model domain. The elevated terrain option was selected.

Surface and upper-air meteorological observations for 2017 were used as input data. The surface dataset mainly corresponds to measurements at a station called Haidian (39.98° N, 116.28° E, ~17 km from the site). Calm winds (~6.2% of the observations) were reset to 0.5 m s^{-1}. Upper air soundings were acquired from the NOAA/ESRL Radiosonde Database for the Beijing Capital International Airport (40.08° N, 116.60° E, ~36 km from the site). The Chinese site has prevailing wind directions (at 10 m height) from northeast (NE) and southwest (SW). The annual mean wind velocity was ~1.5 m s^{-1}.

The application of the two EQs is limited to a single odour source. According to the German guideline VDI 3894 Part 2 [14], in the case of a single source, there will be also only one emission focal point. The present case, however, comprises four sources (i.e., three barns and one feed storage). An overall emission focal point was thus determined on the basis of the coordinates of the individual sources, which are weighted by their respective odour emission rates. Subsequently, the emission focal point of the dairy farm was used as the reference point (origin of the coordinate system) for the separation distance determination.

The German odour impact criterion, as for the Brazilian site, was selected. However, the tolerated exceedance probability of the concentration threshold was taken to be P = 15% because the vicinity of the dairy farm is mostly rural.

3.3. Kittsee, Austria

Separation distances have also been calculated for Kittsee (48.109° N, 17.070° E,), east of Vienna in Austria, near Bratislava [11]. Kittsee is situated within flat terrain, mainly farmland. For this site, separation distances were determined using two dispersion models and then compared to those obtained from the two investigated EQs. The dispersion models used are AODM, a steady-state

Gaussian plume model adapted for odour assessments, and the Lagrangian particle model LASAT. For both dispersion models, an empirical-based peak to mean (p2m) approach, giving the separation distance as a function of the travel distance and atmospheric stability [2,24–26], has been applied as a post-processing tool [44]. This procedure gives two sets of separation distances, namely, one for each dispersion model.

As described before, in Germany, f4 is in use, which is independent of the distance from the source and meteorological conditions [45]. Also, f4 was considered for the two dispersion model outputs, by this means returning two additional sets of separation distance results. Accordingly, for Kittsee, four different model-related sets of separation distances, besides other two related to the investigated EQs, are attained.

A dataset of more than one year of half-hourly ultrasonic anemometer measurements (03.03.2006–31.05.2007) was used. At this site, high wind velocities occurred mainly from NW, often associated with frontal systems and storms. The secondary prevailing winds are from ENE, showing on average lower wind velocities as they are mainly observed in anti-cyclonic conditions. Calm winds frequency was ~0.75% during the period. Calms were discarded. The mean wind velocity of the period was 4.1 m s^{-1}. A single-point source was selected with an odour emission rate of S = 5200 ou_E s^{-1}, 8 m high and vertical exit velocity of 3.0 m s^{-1}.

The German odour impact criterion was used for a protection level of residential areas (*P* = 10%).

3.4. Summary of Input Parameters

The parameters which describe the odour source and the selected dispersion model are summarised in Table 2.

Table 2. Summary of source and site features and input parameters of the three selected case studies in São José dos Pinhais, Brazil; Beijing, People's Republic of China, and Kittsee, Austria, for the selected EQs and dispersion models.

Case Study	Source and Site Features	Input Parameters	Dispersion Model
São José dos Pinhais, Brazil [38]	Single-point source with vertical release Mean wind velocity = 2.9 m s^{-1} Elevations from 880–918 m within the model domain	Odour emission rate S = 15000 ou_E s^{-1} Emission height = 10 m Exit velocity = 3 m s^{-1} Protection level *P* = 10%	AERMOD + f4
Beijing, People's Republic of China [43]	Single-point source with vertical release and three area sources Mean wind velocity = 1.5 m s^{-1} Elevations from 40–55 m within the model domain	Total odour emission rate S = 5850 ou_E s^{-1} Area sources emission height = 0.05 m Point source emission height = 2.5 m Point source exit velocity = 0.5 m s^{-1} Protection level *P* = 15%	AERMOD + f4
Kittsee, Austria [11]	Single-point source with vertical release Mean wind velocity = 4.1 m s^{-1} Flat terrain	Odour emission rate S = 5200 ou_E s^{-1} Emission height = 8 m Exit velocity = 3 m s^{-1} Protection level *P* = 10%	LASAT + f4 LASAT + p2m AODM + f4 AODM + p2m

3.5. Comparison of the Separation Distance Calculated by Dispersion Models and EQs

For the three case studies, Figure 2 depicts the calculated separation distances as contour plots (left panels), and the site-dependent meteorological input data (right panels) as wind roses. The wind roses summarise the wind distribution at the sites, displaying their strength, direction and frequency per 10° sectors over the specified period of data collection. The separation distance shapes resemble to a great extent the wind distribution of the sites. The largest distances tended to occur along with the prevailing wind directions. In other words, the calculated separation distances were significantly influenced by meteorological conditions.

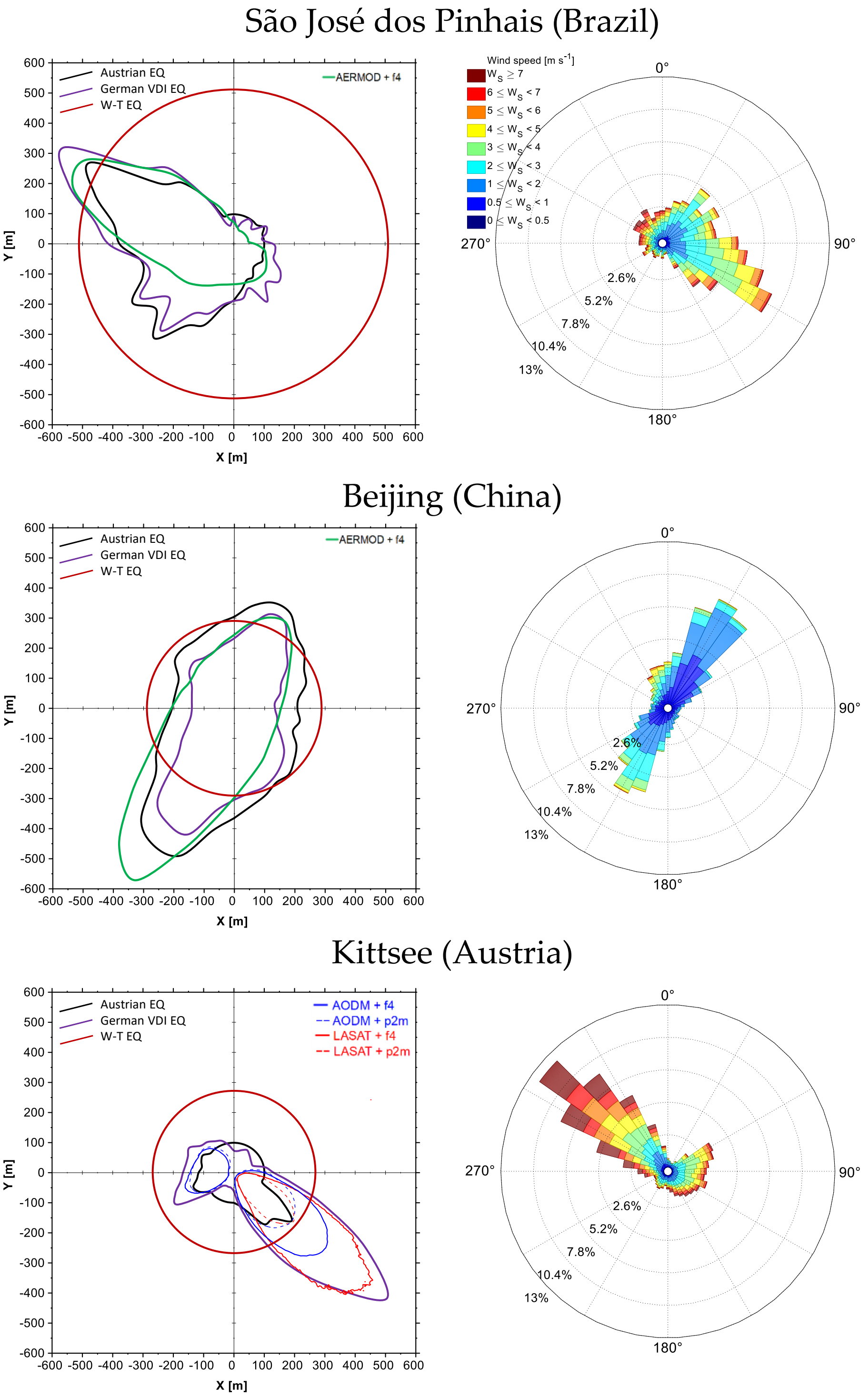

Figure 2. Separation distances calculated using the German VDI, the Austrian, and the W-T EQs against dispersion models for the three case studies under investigation and their respective wind roses.

The first case study is from a site in São José dos Pinhais (Brazil) for which the comparison of separation distances between the AERMOD dispersion model against the two EQs is shown. The conformity of the direction-dependent separation distances derived from these three methods is satisfactory. In this case, the separation distances show a maximum for the two prevailing wind directions, SE and NE, meaning more elongated distances towards NW and SW. For SE winds with a portion of higher wind velocities, the agreement is closer compared to the secondary prevailing wind direction blowing from NE. Moreover, for these NE winds, AERMOD delivers lower distances than the two EQs. The Austrian EQ separation distance pattern towards the 45° sector is due to the limitation to a minimum distance given by this equation. That is, all those separation distances between North and East were reset to 100 m because the Austrian EQ returned smaller values than this minimum, as explained in Section 2. Even if AERMOD was not used to derive the parameters of the two EQs, the shape of the separation distances reflects the meteorological situation of the site in a comparable way.

The second case study is from Beijing (China). Overall, the separation distances show a good correspondence between the two EQs and AERMOD for this case. The Austrian EQ gives generally higher values for the separation distances compared to the German VDI EQ. For the secondary prevailing winds from SW with higher wind velocities, the separation distances of the two EQs and AERMOD show a better agreement compared to the distances related to the north-easterly prevailing wind direction. The wind rose of the site shows high wind velocities for wind directions from N and NW, which results in separation distances towards SE comparable to those in the main wind directions.

The third case study is from Kittsee (Austria). This site features separation distance results from two dispersion models, LASAT and AODM, using the p2m approach, in comparison to the two investigated EQs. While the parameters of the German VDI EQ have been derived using the German regulatory dispersion model AUSTAL2000, the parameters of the Austrian EQ have been derived from AODM calculations. Results applying f4 from [12] are also shown. The first couple (LASAT + f4 and the German VDI EQ) shows a good agreement for the largest separation distances, especially for the NW winds. These large separation distances in the far-field are a well-known effect due to the use of f4. This overestimation for separation distances of several hundred meters was discussed in detail in a previous study [25]. The second couple (AODM + p2m and the Austrian EQ) shows in general a good agreement for the calculated separation distances as well. For the secondary prevailing wind direction from ENE, thus with a transport direction towards WSW, the agreement between the separation distances of the two EQs is much closer. The inconsistency for the NW winds (transport direction towards SE) could be explained by the uncertainty intrinsically related to the estimation of instantaneous ambient concentrations by the p2m approach. For Kittsee, the wind velocity is distinctly higher as compared to the Beijing site. This could be a reason for the higher deviation between the dispersion models and the two EQs in Kittsee.

In accordance with the German OIC [12], the protection level in the Austrian and German EQs is taken into account for a constant odour threshold $C_T = 0.25$ $\mathrm{ou_E\ m^{-3}}$ and an adjustable exceedance probability P (%). In the German guideline, for "commercial, industrial and agricultural areas" and "villages", the exceedance probability is taken as $P = 15\%$. For "residential and mixed areas" as $P = 10\%$. These benchmark exposure limits can be reduced for unpleasant odours and increased for pleasant odours through weighting factors. However, such weighting factors are not considered here. The main condition that was necessary to be followed for the present investigation was to match the exceedance probability P of the odour impact criterion for the two methods (EQ and dispersion models). If a weighting factor for hedonic tone adjustment had been considered, this would return in the end the same P for both methods, thus allowing the separation distances to be compared.

As the emission sources assumed for São José dos Pinhais (Brazil) and Kittsee (Austria) are hypothetical, a reason for selection of stacks and its parameters has to be given. For these cases, we intended to approximate emissions from livestock buildings (mechanically ventilated). In turn, a single-point source was set for each case because it is well known that dispersion models can potentially provide more accurate results for this source typology.

In general, the three case studies demonstrate that the two EQs from Germany and Austria, which include sufficient meteorological data by a 10° wind rose, provide a first guess of the direction-dependent separation distances. Other EQs, which are less elaborated, seem inappropriate for such applications. The consideration of appropriate EQs can be particularly important in the context of tiered regulatory frameworks. If needed, a more detailed investigation using state-of-the-art dispersion models has to be applied.

The case study of Kittsee shows (Figure 2c) a closer relationship between the EQ and the underlying dispersion model with their corresponding peak-to-mean approaches. The dispersion models with f4 show a better agreement with the German EQ. The Austrian EQ, which was derived by using the variable p2m, shows a better agreement between dispersion models using this scheme. In short, it can be seen that the best match is achieved when the peak-to-mean approach that was used to derive the EQ matches with the peak-to-mean approach of the dispersion model.

The W-T EQ was selected for the case studies because it delivers a constant separation distance for all directions. The circle given by this EQ shows that the meteorologically-driven dispersion and transport in the atmosphere cannot be explained by such an oversimplification. Even if this EQ was designed as a worst-case scenario, the separation distances towards the prevailing winds are underestimated for all case studies. Contrary, all the separation distances for wind directions with a low frequency are overestimated. This emphasises that the concept of EQs needs at least a meteorological input based on the wind direction frequency. As expected, the use of 10° wind sectors compared to 45° sectors (as for the old Austrian and the Purdue EQs) shows that this feature improves the separation distance resolution considerably (Figure 2).

4. Discussion

From the list of EQs given in Table 1 and discussed throughout Section 2, the range of empirical methods to give a first guess of separation distances becomes apparent. Simple EQs that do not take into account the meteorological conditions of a site deliver a unique, fixed distance, thereby shaping a circle around the source. More elaborated EQs, especially the Austrian and German EQs, include meteorological predictors (wind direction frequency and average wind velocity per wind direction sector) in their formulations (Figure 1).

Only for the latter case study, the separation distances are compared against those of two different dispersion models using two different peak-to-mean approaches (Figure 2). These EQs employ the highest resolution of the wind direction (thirty six 10° sectors) compared to eight 45° sectors as a separation distance predictor and are consequently considered by the authors to be state-of-the-art. The Austrian EQ also includes the mean wind velocity per wind direction sector as a predictor with the objective of pragmatically considering atmospheric stability. The reason this was considered is centred on the greater variability in atmospheric stability conditions and higher calm frequencies of Austrian sites as compared to most German sites. A simple circular EQ (W-T) was also included in the comparisons shown in Figure 2 to show the remarkable differences in separation distances between EQs considering or not considering meteorology. The impact of the peak to mean approach on the separation distance is here shown only for Kittsee (Figure 2), but was recently discussed more elaborately [46].

The high level of simplifications when using EQs becomes obvious by comparing the indispensable input data for dispersion models and EQs. The characterisation of the emission is reduced to either a constant emission rate or to the number of animals and an odour emission factor to quantify the emission rate. The second approach by the number of animals reduces the applicability of such EQs solely to livestock houses. The German and the Austrian EQs use the odour emission rate, which means that they can also be applied to non-agricultural odour sources. Most of the EQs cannot include the geometry of the emission source (height, vertical velocity, outlet air temperature, area vs. point sources). The highest reduction of input data can be seen for the characterisation of the meteorological situation of a site. For dispersion models, the minimum meteorological input data are usually characterised by hourly values of wind velocity, wind direction, and stability of the atmosphere (with $N = 8760 \times 3 = 26{,}280$ data points), whereas the meteorological input required by the EQs is reduced to the wind frequency distribution for 10° sectors ($N = 36$, German VDI EQ) and mean wind direction for 10° sectors ($N = 72$, Austrian EQ) or even less information (45° sectors with $N = 8$, old Austrian and Purdue EQs). Most of the remaining EQs do not incorporate any meteorological input (Table 1).

The OIC are country-specific; either the odour concentration threshold C_T is held constant and the exceedance probability is adapted to the protection level P, or the other way round with a constant exceedance probability P and a variable odour concentration threshold C_T for a certain protection level. It seems difficult to compare the two approaches but [13] could show that a similarity for the separation distance could be found for various OIC. E.g., the German OIC for pigs in a rural area with $P = 15\%$ and $C_T = 1$ ou_E m^{-3} corresponds to an OIC with $P = 2\%$ and $C_T = 5.4$ ou_E m^{-3}, which is roughly the Irish OIC. This means that the Austrian and the German EQs can potentially be used as a substitute for those countries as well, where the exceedance probability P is hold constant and the odour concentration threshold C_T is adapted to the protection level.

Figure 3 shows a schematic diagram comparing the state-of-the-art procedure to calculate separation distances using a dispersion model against the structure of EQs. It is acknowledged that dispersion models can simulate many more physical processes than EQs and thus often have to be run with more complex input data and parameterisations. In the simplified schematic shown here, both procedures start with the odour emission rate S and end with the direction-dependent separation distance E. The red arrows show the simplifications of the input parameters (meteorology and OIC) in the EQs.

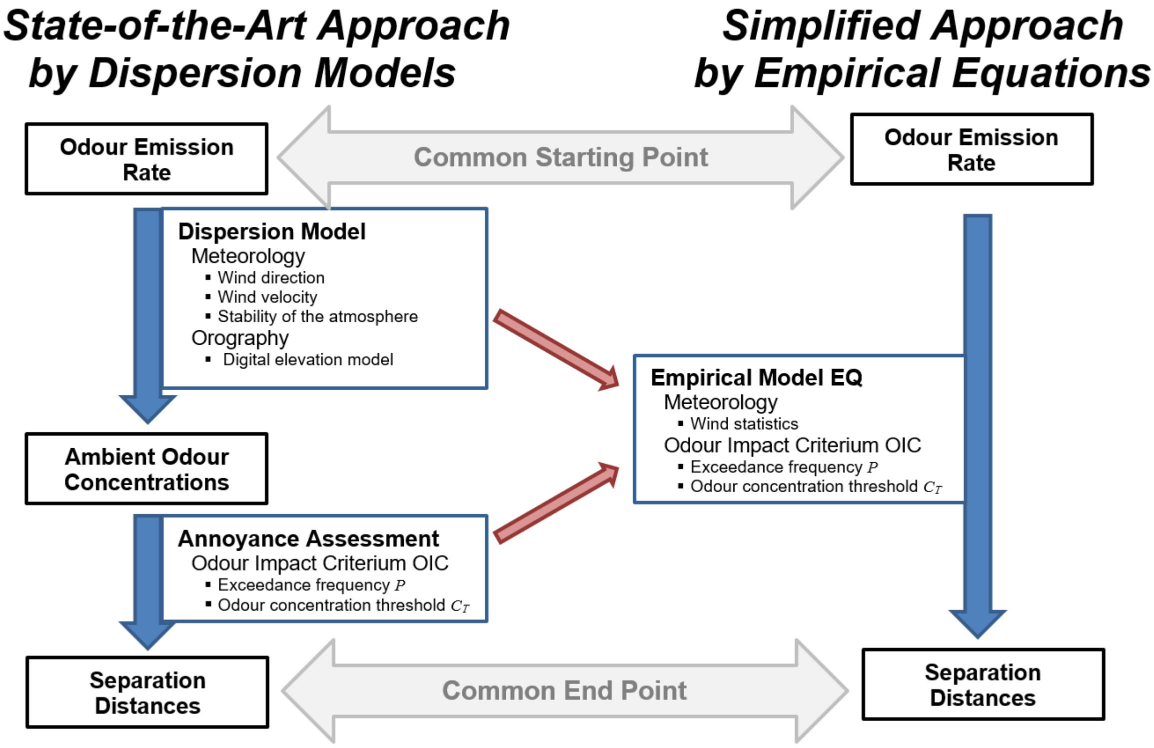

Figure 3. Schematic diagram of the state-of-the-art determination of separation distances by the use of a dispersion model (left side) and the simplified approach shown by the Austrian and German EQs (right side).

A major advantage of using EQs lies in their simplified handling of the influence of meteorological input on separation distances. Dispersion models are typically inputted with annual hourly time series of, for example, wind direction and velocity, atmospheric stability and mixing height. A meteorological dataset with lower temporal resolution (e.g., mean daily data) is not possible, because the OIC, which are needed for the calculation of separation distances, are typically derived for hourly data. Furthermore, atmospheric stability is not routinely measured at standard meteorological stations. Three-axis ultrasonic anemometers, in particular, offer the possibility of estimating atmospheric stability via the Obukhov length, based on wind and turbulence measurements [11,47]. For most of the stability classification schemes, additional non-standard meteorological parameters are necessary to determine stability estimates in the form of classes. The scheme of Golder [48] developed for Turner stability classes (the scheme developed by Reuter [49] is very similar to it) has been used here for AODM. Such a scheme considers sun elevation angle, cloud base height and cloud cover; alternatively, the radiation balance (net radiation) or the vertical temperature gradient, each in combination with the wind velocity, can be used. The details of the schemes are given in Section 4.6 of [50] and in [11].

Conversely, separation distances from EQs are determined by the equation coefficient values, which are derived from a statistical analysis of the time series of modelled ambient odour concentrations by OIC. The EQ procedure includes implicit input of the exceedance probability P to the empirical equations. This means that the two-step procedure of the state-of-the-art modelling methodology is reduced to a single step for EQs.

The German and Austrian EQs are based on model calculations for flat terrain. This means that complex topographical features cannot be considered. The adaptation of meteorological data (wind statistics) to the orographic situation of a site is described in a handbook about the German VDI EQ [23].

Furthermore, most of the existing EQs have been derived for livestock buildings. The odour emission rate related to this sector can be estimated, for example, using emission factors related to the animal species, numbers and body mass, manure handling system, and laying area, among other parameters. These parameters are subsequently used as activity values to scale the odour emission rate. Only those EQs can be applied for other types of odour sources such as wastewater treatment plants and municipal solid waste disposals, which use the odour emission rate ($ou_E\ s^{-1}$) as input parameter.

5. Conclusions

In this work, empirical equations were selected for investigation on the basis that, each in a different and unique manner, they greatly simplify the process of determining the direction-dependent influence of meteorological data on calculated separation distances when compared to dispersion modelling. These EQs are fast and low cost to use. They also meet the requirements that the odour emission rate is quantified in the same way as it is done for dispersion models and separation distances are determined for odour impact criteria as for dispersion models. These constraints allow for a meaningful comparison of empirical equation separation distances against modelled separation distances. In practice, the required meteorological information for the utilisation of the German and Austrian empirical equations are wind statistics in the form of the wind direction frequency distribution and mean wind velocity for 10° sectors (the latter for Austria only).

The investigated empirical equations, developed from simple linear regression models, can potentially calculate distances that are representative of modelling, particularly towards prevailing winds, if the conditions for which they were developed are observed. Otherwise, the empirical equations may give results very different from those provided by dispersion models.

The results suggest that some of the investigated empirical equations can be usefully incorporated as screening-level analysis tools in tiered regulatory odour assessment frameworks. A tiered framework recognises that tools such as simple power function-based equations may be sufficient to demonstrate that a proposal presents a low risk of impacting on amenities at nearby sensitive receptors in some cases. If compliance is demonstrated using such simple screening-level tools, more complex and costly investigations using dispersion modelling might be avoided. In contrast, an assessment using more refined tools such as dispersion models may be required if screening level assessments are not passed.

Author Contributions: G.S.: conceptualisation, writing—original draft preparation; M.B., G.S. and M.P.: methodology; W.K., M.B., G.S., M.P. and C.W.: preparation of input data and modelling; G.S., M.P., K.D.G. and

M.B.: writing—review and editing; M.B., G.S. and M.P.: projects' administration; M.B., G.S., M.P. and C.W.: funding acquisition; G.S. and M.P.: supervision. All authors have read and agreed to the published version of the manuscript.

Funding: Marlon Brancher is supported by the Austrian Science Fund (FWF) in the framework of the Lise Meitner Programme [project number M 2548-N29]. We also thank the National Key R&D Program of China (Nos. 2016YFC0700603, 2016YFC0700600 and 2016YFE0115500), the National Natural Science Foundation of China (21576023), and the Fundamental Research Funds for the Central Universities (No. FRF-TP-17-047A1). The cooperation between Austria and China was funded by the OeAD-GmbH (No. CN 10/2016).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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