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A Smart Fuzzy System Applied to Reduce Odour Production from a Waste Landfill

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Control and management of odours from landfills is becoming a relevant topic for both the public and the technical community, as numerous landfills are located nearby highly urbanised areas. The attention is focused on how odour emissions can be managed and mitigated to reduce the odour nuisance. This paper proposes a Smart Fuzzy System (SFS) to mitigate the odour production of a solid waste landfill, called "Cava del Cane", in North of Naples (Italy), as the area surrounding the landfill is densely populated, with the presence of hospitals, schools, and sports centres. The SFS proposed is based on a fuzzy approach that, via a certain number of input variables (i.e. the direction, the intensity and variation of wind), allows to obtain the mitigation actions to be applied in a landfill (e.g., waste covering, spraying of perfumed substances, placement of extraction wells to maintain waste under pressure, etc.) in order to reduce its odour emissions. The odour transport modelling was carried out by using CALPUFF model (U.S. Environmental Protection Agency (U.S.EPA)). CALPUFF allowed to assess the dispersion of odours in air as a function of the odour emission rates from the landfill and the weather conditions of the area. The input variables considered in the SFS were described via some "membership functions", and the mitigation actions (output) were inferred by using a set of 16 fuzzy rules based on human expertise. The fuzzy system was optimized by using a Genetic Algorithm (GA) with some constraints to preserve the physical meaning of all parameters considered. The simulation results showed a good effectiveness of the SFS, as a significant reduction of threshold exceeds was obtained in the whole area.

1. Introduction

Odour production from landfills is related to the aerobic and anaerobic biodegradation processes of putrescible waste. The chemical composition and intensity of odour emissions are due to a mixture of substances developing in the wastes where reactions continuously occur approaching thermodynamic equilibrium (Lancia et al., 1996). Odorous emissions are extremely variable in flow rate and concentration and characterized by alternative periods of high and low emissions (Drew et al., 2007). Exposure to landfill odours may cause annoyance on the population or odour nuisance, when there is a cumulative effect of repeated events of annoyance over an extended period of time. Short-term exposures occurring at high concentrations cause more annoyance impact on the population than constant exposures at long-lasting concentrations. This is because the human sense of smell tends to adjust to the external conditions (GOAA, 1999).
The main technologies to control odorous emissions include bio-filters (Sun et al., 2000), adsorption on activated carbon (Karatza et al., 1996; Erto et al., 2010) and scrubbing with Advanced Oxidizing Process (AOP) (Smet et al., 1998, Lancia and Musmarra, 1999; Capocelli et al., 2012), but these may be not applicable to the treatment of high and disseminated emissions as the kind of emissions of waste landfills. In those cases, prevention of odour impact can be achieved using one or more of the following expedients: (1) progressively cover deposited waste with a suitable layer of daily cover material (e.g. clay) at least thicker than 0.2-0.4m; (2) ensure a gas extraction wells system to collect the landfill bio-gas and to maintain the landfill body under pressure, with treatment of gas extracted via suitable bio-filters; (3) use

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water containing specific enzymes and/or odorant and spray them on the waste surface in the most critical cases. The use and the level of the “activation” of each control expedient depend on some input variables (e.g. source emissions, local meteorological conditions, distance of sensitive centres, etc.) and on the feasibility of the system, allowing also an optimization of the actions adopted to reduce the odorous emissions.
In this paper an innovative tool, based on fuzzy logic called Smart Fuzzy System (SFS) (Dubois and Prade, 1980) is presented. The SFS helps to automatically mitigate the annoying smell coming from a municipal solid waste. In the classical approach of optimization problems, decisions are generally based on several different considerations, often difficult to explain with mathematical equations (Di Nardo et al., 2012; Cavallo et al., 2013). Hence a purely model-based approach would be extremely complicated to apply for this type of decision problems, a fuzzy logic can be very useful. The approach based on fuzzy logic showed to be fundamental to formalize the management of the empirical rules adopted, and to integrate them into an automated decision support system. In this way, it was possible to consider different inhomogeneous considerations (i.e. whether conditions) in a unique rules framework, that represents the core of management activity. In addition, the fuzzy approach proved also to be very effective both for its peculiar capability to deal with nonlinear models, and for the possibility to take into account heuristic rules.
The SFS proposed in this paper is an improved version of a preliminary fuzzy system presented in Di Nardo et al. (2013), as the fuzzy inference was optimized with a significantly increase of the mitigation of risk exposure for the surrounding population. The SFS was implemented in MATLAB framework integrating the FUZZY LOGIC and OPTIMIZATION Toolbox (The MathWorks Inc. 2004a) and CALPUFF software (Earth Tech and Inc., 2000; U.S. EPA, 1995) was used to simulate the atmospheric transport of the odorous emissions.

2. Smart Fuzzy System

The SFS is based on a complex fuzzy inference system that, as known in the literature, turns numeric input through linguistic knowledge into numeric output. In this study, the following Sugeno-type rule system (Sugeno 1985) were obtained by using the l-th rule , where l=1,…,r=13 rules, as shown in the following:

$$R^{(l)}: IF\ x_1\ is\ P_1^{(l)}\ AND\ x_2\ is\ P_2^{(l)}\ and\ x_3\ is\ P_3^{(l)}\ THEN\ y = C_1 \quad (1)$$

where the input variables x_1, x_2 and x_3 are the main physical quantities affecting the dispersion of pollutants in the atmosphere, equal respectively to the wind speed, the time derivative of velocity and the wind direction; y, instead is the output linguistic variable related to the hourly emission factors, that represents a possible reduction of emissions, achieved by activating the expedients presented in the previous section.
Specifically, in Equation (1), P_i is the fuzzy set referred to the i-th input linguistic variable, where i=1,…,3, with the following attributes: P_1={weak, normal, strong}, P_2={low, zero, high}, P_3={North, North-East, East, South-East, South, South-West, West, North-West}. While C_1 is the output set modelled by a singleton membership function (Sugeno, 1985) with the following attributes C_1={normal, bad, very bad} corresponding to normal=8 o.u./m^{2}s, bad=4 o.u./m^{2}s and very bad=2 o.u./m^{2}s.
Starting from the empirical knowledge of the problem and from the previous preliminary results (Di Nardo et al., 2013), a first choice of the shape of the membership functions and of the rule inference system were defined. Then, in order to improve the performance of the fuzzy strategy, an optimization procedure was carried out. Specifically, 11 parameters of the input membership functions (with the exception of the fuzzy set P_3) were optimized via using a Genetic Algorithm (GA) (Goldberg,1989), therefore minimizing the following Multi Objective Function (MOF):

$$MOF = k_1 \cdot \frac{C_{SFS}}{C_{cost}} + k_2 \cdot I_a \quad (2)$$

where k_1=2 and k_2=1 are integer weights to balance the two terms of MOF and prevent the optimization of only one element; C_{SFS} and C_{cost} are the olfactory concentrations produced by the landfill, and computed via using CALPUFF, with odour emission factors of provided by SFS and by considering a constant emission over time, equal to 8 o.u./m^{2}s; this latter represents the average emission of the landfill without any mitigation action; I_a is the activation index defined as follows:

$$I_a = \frac{N_a}{N_h} \quad (3)$$

where N_a is the number of SFS system activations (the number of times in which SFS operates with an odours reduction by considering one or more expedients) and N_h is the total number of hours of the simulation period. The GA solution was obtained with 50 generations and with a population composed of 50 individuals with a crossover percentage P_{cross}=0.8.
The optimization phase was carried out by using MATLAB/OPTIMIZATION Toolbox (The MathWorks Inc., 2004b). The computation of odours transport in the environment surrounding a municipal solid waste landfill was analyzed by CALPUFF, a non-steady-state Lagrangian Gaussian puff model (U.S.EPA, 1995; Earth Tech and Inc., 2000). CALPUFF allows to simulate the transport of a puff of material emitted from modelled sources, also considering the dispersion and the transformation mechanisms. The basic equation for the contribution of a puff at a defined receptor is written as:

$$C = \frac{Q}{2\pi\sigma_x\sigma_y} g \exp\left[\frac{-d_a^2}{2\sigma_x^2}\right]\exp\left[\frac{-d_c^2}{2\sigma_y^2}\right] \tag{4}$$

where C is the ground level concentration expressed in g/m^3, Q is the pollutant mass, σ_x, σ_y and σ_z are the standard deviation of the Gaussian distribution in the along-wind direction, in the cross-wind direction and the vertical direction respectively, d_a and d_c are the distance from the puff centre to the receptor in the along wind direction and in the cross wind direction, respectively, g is the vertical term of the Gaussian equation described by the following equation:

$$g = \frac{2}{(2\pi)^{1/2}\sigma_z}\sum_{n=-\infty}^{\infty}\exp\left[\frac{-(H_e + 2nh)^2}{2\sigma_z^2}\right] \tag{5}$$

In Equation (5), H_e is the effective height above the ground of the puff centre and h is the mixed-layer height. In this study, the meteorological data file is a single-station meteorological data in ISCST3 data format (Trinity Consultants Incorporated, 1996). The meteorological data file includes hourly values of the following vectors: wind direction, wind speed, temperature, stability class and mixing height.

3. Case study

The methodology proposed was applied to a municipal solid waste landfill located at a mine, named "Cava del Cane", and located in North of Naples (Bortone *et al.*, 2012). As it is possible to see in Figure 1, the area surrounding the landfill is densely urbanised, and several villages, schools, hospitals, and leisure and sports centres are present. In particular, three Sensitive Centres (SC) were identified in the interest area for their proximity to the landfill and the risk exposure to odours, called SC-1 "Monaldi" hospital; SC-2 "Marano" school; SC-3 "Kennedy" sports complex and located at 800m, 1,300m and 1,500m from the landfill, respectively.
The emission source was placed in the centre of the landfill and the emissive surface was assumed conservatively equal to the total area of the landfill, approximately 12,450 m^2. The flow rate of odorous substances was modelled by using a constant emission factor equal to 8 u.o./m^{2}s (Sironi et al., 2005). In this study, the meteorological data of the year 2007 were provided by the closest monitoring station (AM 289-Capodichino) and the value of 1.5 o.u./m^3 and 3.0 o.u./m^3 concentrations, on the 98th percentile hourly basis (IPPC, 2002), were considered as a reference thresholds for the assessment of odour dispersion from the landfill.
In order to optimize the SFS, the meteorological year data were divided into four quarters and used to prepare the SFS system and validate it. In particular, the first quarter was chosen as "training data", while the second, the third and the fourth quarters as "validation data".
Starting from the rule set shown in Figure 2a, the optimization procedure provided the input membership functions illustrated in Figures 2b, 2c and 2d.
In order to evaluate the effectiveness of SFS, some performance indices were also considered, alias the 95th and 98th percentile concentrations, the Number Of Exceedances (NOE) over the thresholds of 1.5 o.u./m^3 and 3.0 o.u./m^3, the activation index, I_a, and the reduction index, I_r. This latter described by the following equation:

$$I_r = \frac{C_{Cost} - C_{SFS}}{C_{Cost}} \tag{6}$$

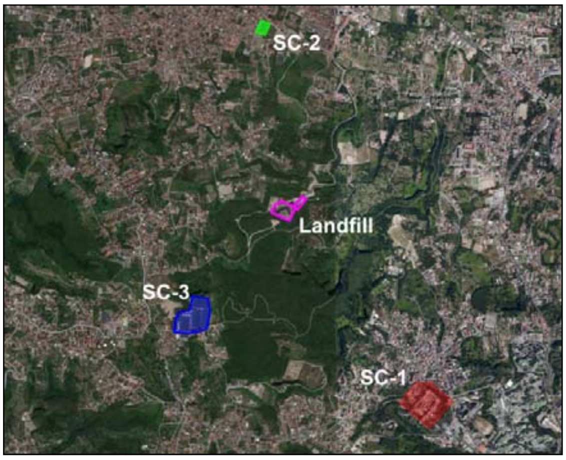
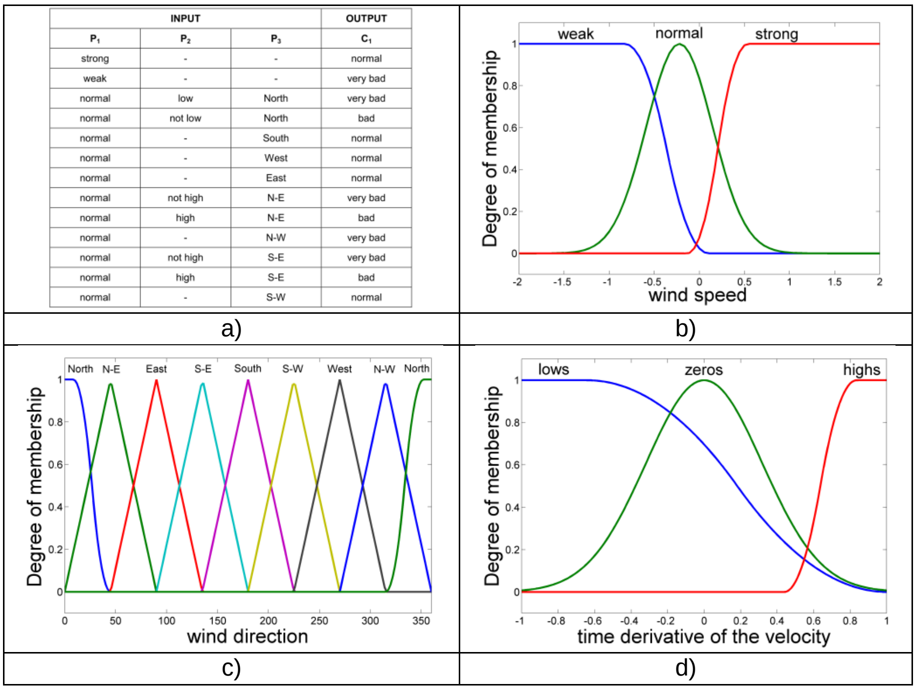


Figure 1: Study area with the location of the landfill and of the sensitive centers

For each SC, the performance indices were computed both for the emissions controlled by the fuzzy system and for emissions without using it. The results obtained are reported in Tables 1, 2, 3 and 4.



INPUT			OUTPUT
P_1	P_2	P_3	C_1
strong	-	-	normal
weak	-	-	very bad
normal	low	North	very bad
normal	not low	North	bad
normal	-	South	normal
normal	-	West	normal
normal	-	East	normal
normal	not high	N-E	very bad
normal	high	N-E	bad
normal	-	N-W	very bad
normal	not high	S-E	very bad
normal	high	S-E	bad
normal	-	S-W	normal

Figure 2: Fuzzy Rule Set and Optimized Membership Functions of SFS

The analysis of the results showed that for the three sensitive centres, the olfactory concentration exceeded both the 1.5 o.u./m^3 and 3.0 o.u./m^3 thresholds and also the concentration at the 98th percentile were always above the reference limit. In addition, the odour concentrations over the time computed via CALPUFF software, were also compared with the odour concentration values obtained by using ISCST3-BREEZE model of the previous study considered (Di Nardo et al., 2013), showing values higher in the computational domain confirming the result obtained by Wang et al. (2006).

However, the SFS allowed a considerable reduction in the number of exceedances. In particular for the 1.5 o.u./m^3 threshold, the number of exceedances decreased of about 97% in SC-1, of about 96% in SC-2 and about 51% in SC-3; for the threshold 3.0 o.u./m^3, instead, there were no exceedances both in SC-1 and SC-2, while in SC-3 was noticed a decrement of about 90% of it. With reference to the concentrations at the 98th percentile and at the 95th percentile (Table 1 and Table 2, respectively), the values of odour concentrations in SC-1 and in SC-2 were significantly lower than the limit (1.5 o.u./m^3) by using the SFS, while these exceeded the threshold without any mitigation action. As shown in Table 3, SC-3 is the sensible centre with the highest number of exceedances, consequently it resulted to be more exposed to the smell harassment, also because it is the closest to the emissive source. Although the SFS system allowed a significant reduction of the number of exceedances, the concentrations at the 98th percentile and at the 95th percentile are not always lower than both the thresholds considered. In the last quarter of the validation set, the concentrations at the 95th percentile obtained were lower than the 1.5 o.u./m^3 threshold.

Table 1: SC-1 results both in case of active fuzzy controller (SFS) and without it (C_{Cost})

	NOE > 1.5 [o.u./m^3]		NOE > 3.0 [o.u./m^3]		98th percentile [o.u./m^3]		95th percentile [o.u./m^3]	
	C_{cost}	SFS	C_{cost}	SFS	C_{cost}	SFS	C_{cost}	SFS
Training Set	77	1	1	0	2.09	0.62	0.59	0.23
	67	1	6	0	2.18	0.63	1.23	0.38
Validation Set	92	1	3	0	2.10	0.67	0.95	0.32
	63	7	1	0	1.82	0.51	0.29	0.11
Total Set	299	10	11	0	2.07	0.62	0.66	0.22

Table 2: SC-2 results both in case of active fuzzy controller (SFS) and without it (C_{Cost})

	NOE> 1.5 [o.u./m^3]		NOE> 3.0 [o.u./m^3]		98th percentile [o.u./m^3]		95th percentile [o.u./m^3]	
	C_{cost}	SFS	C_{cost}	SFS	C_{cost}	SFS	C_{cost}	SFS
Training Set	101	2	27	0	2.63	0.78	1.27	0.56
	78	1	11	0	2.52	0.74	1.58	0.58
Validation Set	105	3	20	0	2.52	0.78	1.37	0.47
	77	9	15	0	2.30	0.74	0.88	0.40
Total Set	361	15	73	0	2.50	0.77	1.20	0.48

Table 3: SC-3 results both in case of active fuzzy controller (SFS) and without it (C_{Cost})

	NOE> 1.5 [o.u./m^3]		NOE> 3.0 [o.u./m^3]		98th percentile [o.u./m^3]		95th percentile [o.u./m^3]	
	C_{cost}	SFS	C_{cost}	SFS	C_{cost}	SFS	C_{cost}	SFS
Training Set	273	136	215	24	6.17	2.27	4.22	1.61
	200	85	167	8	6.13	2.14	4.80	1.56
Validation Set	268	139	211	19	6.16	2.24	4.39	1.62
	217	111	173	25	5.58	1.87	3.28	1.15
Total Set	958	471	766	76	6.06	2.15	4.07	1.54

Finally, in Table 4, the reduction index, I_r, and the activation index, I_a, were reported. The comparison between the two indexes allowed the identification of the more effective activations in order to avoid to exceed both the odour thresholds in all sensitive centres. The best values of the reduction index resulted equal to 70%, and it was obtained in SC-1 while the activation index was equal to 60%; corresponding to the activation of the SFS system for about 5,200 hours in a year.

Table 4: Reduction index (I_r) and activation index (I_a) for the three SC

	I_r [%]			I_a [%]
	SC-1	SC-2	SC-3	
Training Set	71	70	63	62
	71	71	65	62
Validation Set	68	69	64	56
	72	68	67	61
Total Set	70	69	65	60

4. Conclusions

In the present study a Smart Fuzzy System (SFS) for early warning, as a real-time decision-making support tool to mitigate annoying odours from waste landfills, is proposed. The application of the SFS to the real case of the “Cava del Cane” landfill, near Naples, provided a significant reduction in concentrations in all the three sensitive centres considered with a number of SFS activation slightly higher

than 50%. The optimization of the fuzzy system by using a GA algorithm allowed to significantly improve a fuzzy system previously proposed by the authors.
New multi objective functions and more fuzzy parameters for optimization process are in progress in order to improve further the mitigation of the risk exposure.

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