THE USE OF DISPERSION MODELING FOR URBAN AIR POLLUTION MANAGEMENT

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SUMMARY

A decision support system (DSS) under development for urban air management is outlined. One of the key issues in the system is the model describing the dispersion of the pollutant in the atmosphere. A new model concept is presented, where the influence of single street canyons on the dispersion phenomena is taken into account in a simplified manner. A preliminary analysis of the town of Messina (Sicily) indicate that the model is capable to give at least consistent results. Through the construction of preliminary indicators the model results are translated and introduced in the DSS.

Keywords: Risk assessment, decision support, dispersion models, air pollution, urban area

1. INTRODUCTION

The management of urban air pollution problems is a complicated issue, requiring first of all a sufficient detailed set of territorial data for the urban area in question (territorial topography, building topography, sources, wind, etc.), secondly a methodology for the construction of scenarios, thirdly a (set of) models for the prediction of the dispersion of the air pollutant over the territory, and finally a decision support methodology capable of integrating the various modules and presenting the (salient) choices to the decision-maker.

If the decision maker needs information about direct health effects (short term or long term) also methodologies for the prediction of such effect, based on the output of the dispersion model, is needed.

All in all a complex set of data, models and support tools need to be integrated in order to provide the decision maker with sufficient knowledge to be able to manage the problem in an integrated way.

For the town of Messina in Italy, such a system is under development[1]. This development will be described in the following, starting with a description of the project.

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2. URBAN AIR POLLUTION PROJECT

In the frame of a research project carried out in collaboration between the Joint Research Centre Ispra, the region of Sicily and the 3 universities of Messina, Catania and Palermo a detailed study of the air pollution phenomena and problems is being done. The project involves the measurement of the concentration of pollutant in a number of positions in the urban area, the development of prediction models and the integration of the models and results in a information system aimed at supporting decisions on the problem.
In all three cities, a measurement campaign is currently underway, with passive sensors measuring the average concentration of NO_x in a fine grid in the city centres. For Messina, the position of the measurements stations are shown in Figure 1.

Figure 1. City of Messina with measurements stations indicated (⊕).

The measurements will serve as calibration data for the air pollution dispersion model described in detail later.
The tight link to the data will mean that the model predictions and thus the decision support system could be extendible in a later phase towards real time application.
The starting point for the evaluation of the air pollution dispersion is the lay-out (geography) of the city.

3. DECISION SUPPORT SYSTEMS

A DSS is an "interactive system, flexible and adaptable, which uses decision rules, models, data bases and suitable formal representations of the decision maker(s)'s requests to indicate specific and applicable actions to solve problems which cannot be solved by the optimisation models of classical Operational Research. It thus assists complex decision processes and increases their efficiency." (Paruccini, 1994)

It is clear that the DSS is based on a computer, working on-line with the user, preferably with suitable graphic representations.

DSS generally include three subsystems which can interact: user-interaction subsystem, data subsystem and model subsystem. These subsystems schematise the three basic elements of a DSS: the data banks, the models and the interface software which allows the user to interact with the data bases and the models.

More precisely the user-interaction subsystem module consists of a back-end with the control software and data base integration and models and a front-end with the software for controlling the interface between the user and the system.

Finally decision support systems must possess an open modular system which allows easy integration in the system of new data and specific models which have been previously and independently developed.

A diagram which describes the general system architecture indicating its functional specifications is shown in Fig. 2.

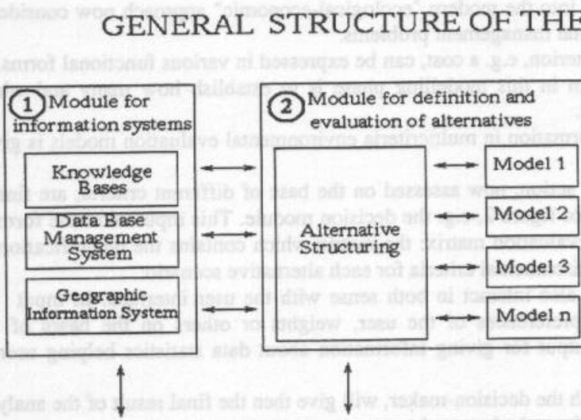

Figure 2: Decision Support System scheme

The information system must be designed for the questions of issues pertaining to a specific problem at a specific site, within a specific region. It is contained in the first module, made up of different and differently structured data bases: possibly a knowledge base for the use of expert systems and certainly a Geographical Information System (GIS). These data can be processed and, when interrogated by the user, shown on the screen or printed on tables and graphs.

Modelling must evaluate the various alternatives of action with suitable time scale, quantifying relevant parameters such as the rate of economic development, energy consumption, the evolution of production technologies and the adjustment between resident population and employees to production activities, and so on.

The second module in the DSS diagram given in Figure 2 deals with the construction of various alternatives of action and gives a specific quantitative evaluation for each of these.

This involves integrating in sets which are consistent, feasible and alternative, the possible operations for improving the management and use of the body which is the subject of study.

The selection of the most suitable criteria can be effectively defined when one has a concrete case and a real user. These are in fact the decision variables which the decision maker can influence directly. They must be specified and related by means of mathematical functions forming the objectives and the constraints.

One can however indicate the criteria generally taken into consideration divided into two broad families:

1. Social and Economic
2. Environmental

This classification fits well into the modern "ecological-economic" approach now considered fundamental in environmental management problems.

Obviously each specific criterion, e.g. a cost, can be expressed in various functional forms, so that a fundamental problem in this modelling phase is to establish how many and which functions (models) to adopt.

The treatment of fuzzy information in multicriteria environmental evaluation models is given in (Munda, 1995).

The various alternatives of action, now assessed on the base of different criteria, are finally passed to the third module of figure 2, e.g. the decision module. This input takes the form of the so-called multicriteria evaluation matrix: the matrix which contains the quantification of the socio-economic and environmental criteria for each alternative scenario.

The decision module must also interact in both sense with the user interface. In input for having information about preferences of the user, weights or others on the bases of the method implemented; in output for giving information about data statistics helping user to shape his preference.

The module, interacting with the decision-maker, will give then the final result of the analysis as a ranking of alternatives from the best to the worst.

To enable the decision-maker to interact usefully, the criteria comparison using the preferences is a fundamental task. It is implemented by different multicriteria methods in different ways.

Multiple Criteria Decision techniques, for any type of problem, are formally solved by through the following operations:

1. Choice of a set of evaluation criteria;
2. Choice of a set of alternatives;
3. Identification of the decision maker's system of preference;
4. Modelling of the preferences;
5. Choice of a criteria comparison method.

An overview of multicriteria methods on environmental management is given in (Paruccini, 1994).

The result of the processing of the decision model normally consists in a ranking: i.e. the alternatives presented in the comparison are ranked from best to worse on the basis of decision criteria adopted, and on the structuring of the decision maker's preferences made differently depending on the method chosen.

4 DISPERSION MODELS

The requirements to a dispersion model in a management system are very severe. The model has to be sufficiently accurate so the calculational results are not only qualitative but also a quantitative acceptable. However, due to the large number of scenarios to be handled, the CPU time required for a single calculation has to be rather limited. Below is given an outline of existing types of dispersion models and of the new approach.

4.1. Existing Models

During the last 10 years models for dispersion of gases in build-up areas has been developed by numerous research teams. These models range from simple analytical tools to very detailed 3-dimensional computational fluid dynamics (CFD) codes. The CPU times (on a workstation or a powerful PC) required to calculate a typical scenario range from fractions of a second to weeks. The models can be categorized in different types and are mentioned below in an increasing order of complexity and computer requirements (CPU time and memory).

4.1.1. Analytical Models

The most simple models are the Gaussian ones based on the analytical solution of the diffusion equation.

The concentration in case of a continuous release is often calculated by means of the following type of formula:

$$c(x,y,z)=\frac{Q}{2\pi u\sigma_y(x)\sigma_z(x)}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y(x)}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z(x)}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z(x)}\right)^2\right]\right\} \quad (1)$$

where Q is the source strength, u is the wind velocity, H is the source height, σ_y and σ_z are the lateral and horizontal spread parameters, respectively. The latter two are normally (non-linear) functions of the downwind coordinate x.

The above mentioned equation is normally applicable for flat terrain without any obstructions. However, the influence of buildings around the source on the far-field can to a certain extent be modeled by a horizontal shift in the source position, see e.g. (Theurer, Bächlin, Plate ,1992).

Due to the analytical approach, the computer requirements for these models are very limited.

4.1.2. Box or Shallow Layer Models

These models are based on a approximate numerical solution of the diffusion-convection equation. The spatial variation of the cloud properties in 0, 1 or 2 dimensions is calculated by a numerical solver. The variation in the other dimensions (3, 2, or 1) is calculated analytically by means of expressions as eq. (1).

In case of 0-dimensional models (box-models), the shape of the cloud is assumed a priori (e.g. a cylinder for an instantaneous release). The cloud height, diameter (or width), velocity and concentration are regarded as bulk properties.

In the shallow layer models the variation of properties in the vertical direction is assumed less important than in the horizontal directions, so the properties are integrated over the cloud height.

In the 1-D models the variations of the cloud height, width, concentration, and velocity are calculated in the downwind direction. The 2-D models also calculate the variation of cloud properties in the cross wind direction.

The interaction between the cloud and surrounding atmosphere is modeled by means of entrainment velocities. These describe the rate by which air enters and dilutes the cloud.

The 1-D models can only handle simple obstructions (e.g. straight, infinite fences), whereas it is possible to include buildings in a 2-D calculation. However, it is not (at least not at present) feasible to model a large urban area for an extended period of time (e.g. one month) with this kind of model, due to huge computer requirements.

4.1.3. CFD Models

The computational fluid dynamics models are the most detailed and complex dispersion models. They solve the fully 3-dimensional Navier-Stokes equations, where the influence of turbulence is modeled by means of turbulent eddy viscosities. These viscosities are normally functions of the turbulent kinetic energy (and in case of the so-called k-ε models, also the turbulent energy dissipation). Additional partial differential equations are therefore needed to describe these parameters.

The influence of buildings is normally described by blocked cells, so the simulation of an urban area would require a huge amount of computational cells. However, there are also models where several buildings can be modeled by one cell. An example is the ADREA code (Bartzis, 1991) which operates with cell porosities and permeabilities. However, in this context, the computer requirements for this kind of models, are still prohibitive.

4.2. Present Model.

The present model is a new approach to predict the influence of buildings on dispersion. The gas cloud is assumed to be convected with the actual wind velocity in a 2-dimensional, horizontal grid. The number of grid points is larger than usually applied in the above mentioned existing models, so a detailed description of the urban area is possible.
In fact, the grid applied corresponds to the pixel information contained in a graphical information file of the town.
In the actual example for Messina, the grid consists of 583 times 423 cells (or pixels), each of the size 10 m times 10 m. Thus the total area modeled is about 24.7 km^2 The streets and open areas are modeled by fully open cells, whereas buildings are modeled by fully blocked cells.
In order to keep the CPU times at a reasonable level, rather simple assumptions have been made in describing the interaction between the cloud and buildings. In case of fully open cells the contents of gas in a cell is assumed to be convected to two neighboring cells (one lateral cell and one corner cell) in the downwind direction.
The partition of gas between the two cells is in the present version defined by the following equations, derived from geometrical considerations (cf. Fig. 3):

$$F_{\max} = \frac{\cos\phi - \sin\phi}{\cos\phi + \left(\sqrt{2}-1\right)\sin\phi} \quad (2)$$

$$F_{\min} = \frac{\sqrt{2}\sin\phi}{\cos\phi + \left(\sqrt{2}-1\right)\sin\phi} \quad (3)$$

where ϕ is the angle between the wind direction and the nearest 45 degree line. Thus ϕ is in the interval [0;22.5°].
In case of one or more blocked cells in the downwind direction, the calculated fraction (F_{max} or F_{min}) either remains at the original cell, or is convected to an alternative cell. Examples of the strategy applied for different blocked cells is given in Fig. 4.
The magnitude of the wind velocity defines the distance (the number of cells) the gas in a certain cell is convected in one time step.
Presently, the height of the cloud is assumed to be constant and equal to the average building height. Thus the amount of air from the surroundings that entrains into the cloud is determined by this constant cloud height.
A more realistic approach would be to describe the mixing of air by means of a top entrainment velocity. This velocity is the rate the cloud height increases due to the entrainment of air at the top of the cloud. In (Würtz, 1993) it was found that for 1-D shallow layer models it could be described adequately well by:

$$W_e = 0.03\,u \quad (4)$$

where W_e is the entrainment velocity, and u the cloud velocity (which equals the wind velocity). It is planned to adopt this approach in the next version of the model.
The pollutant sources are at present all assumed to originate from the traffic. They are all line sources located in the streets of the town. A number of different source rates are assumed, depending of the character and location of the streets. The daily variation of the emission rates is also taken into account.

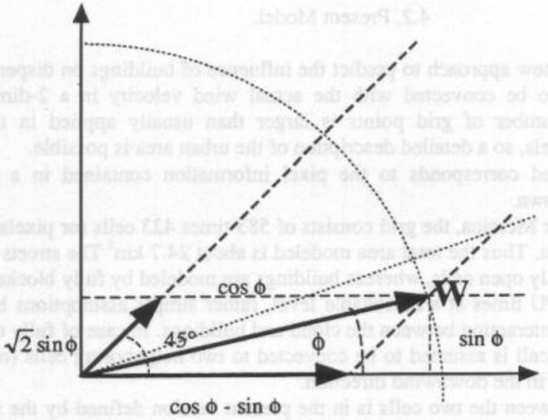

*Fig. 3. The components of the wind vector **W** as a function of the angle φ. Applied for the derivation of eqs. (2) and (3).*

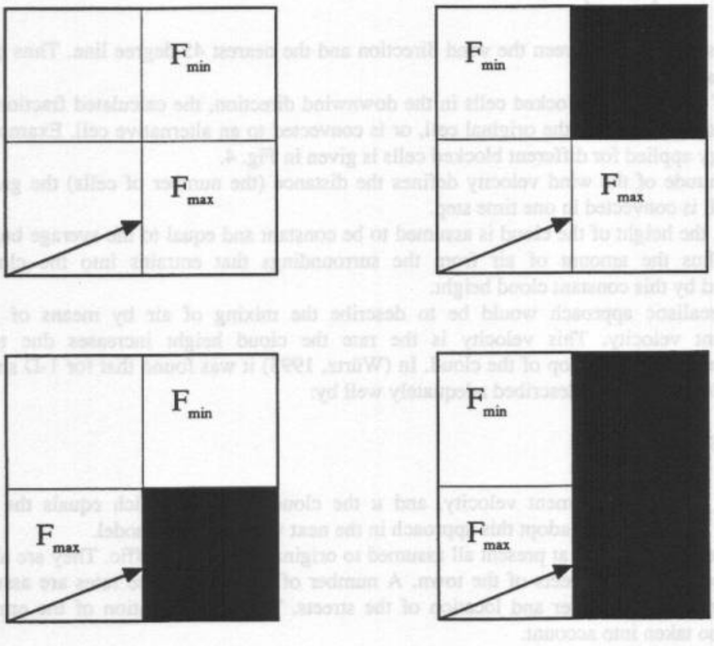

Fig. 4. Examples of the distribution strategy of the fractions F_{max} and F_{min}.

5. PRELIMINARY RESULTS

Some preliminary results obtained with the above described model will now be presented. The model was run for one day only (10th January 1994), and the calculated concentration distributions are shown at midnight (between 10th and 11th). The actual wind direction varied during the day from South-East (midnight) via South-West (1 p.m.) to North (midnight). The wind velocity varied from 11 m/s (midnight) via 4 m/s (7 a.m.) and 7 m/s (7 p.m.) to 6 m/s (midnight).

Three different maximum source intensities were assumed, corresponding to major thoroughfare streets, main streets and side streets. The intensity was varied during the day from 10 % (of maximum) at midnight via 80 % (at 8 a.m.), 60 % (at 11 a.m.), 100% (at 19 p.m.) to 10 % (at midnight).

In Fig. 5 the result of the base case is shown. Due to the prevailing (South-Western) wind direction the pollutant is mainly dispersed in direction of the sea. It is seen that the highest concentrations are found in the street canyons, whereas the concentration is reduced drastically in case of open surroundings (compare e.g. the two parallel major thoroughfare streets heading North-South close to the sea).

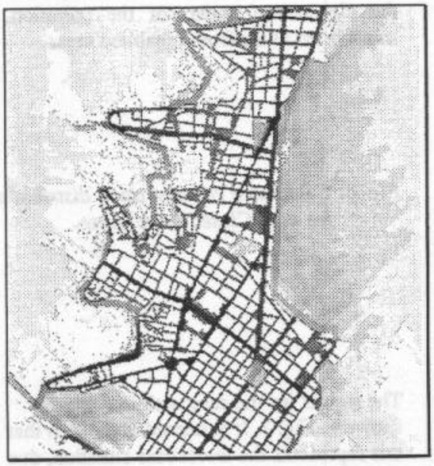

Fig. 5 Calculated concentration distribution for the "Base Case"

4 scenarios has been examined. The characteristics (in comparison with the base case) are as follows:

1 Reduced Traffic: The traffic intensity is reduced 30 %.
2 Increased Traffic: The traffic intensity is increased 30 %.
3 Closed Area: The town centre is closed for traffic.
4 Low Wind: The wind velocity is reduced to 1 m/s.

The "Reduced Traffic" case could be realised if traffic restrictions based on the parity of the license plates (only cars with even numbers on even dates, and vice versa) is introduced. The "Closed Centre" (maybe to a smaller extend than indicated here) could of course be realised by the introduction of pedestrian streets.

The wind field in the first three cases is identical with the base case. In the 4th case the wind direction is assumed to turn 360 degrees during the 24 hours. The wind speed is assumed constant to be 1 m/s.

The traffic pattern in the last case is identical with the base case, whereas the intensities are changed in the two first. In the third case the intensity in a central part of the town (see Fig. 6) is set to zero. In order to take into account the increased traffic on the circumferential roads, the intensity on these roads is tripled.

The results for the two first cases are very similar to the one shown in Fig. 5. They only differ in terms of concentration level.

The results for the "Closed Area" case is shown in Fig. 6. It is seen that the concentration in the central part of Messina is drastically reduced due to the removal of the traffic. The tripling of the traffic on the circumferential road creates not only an increase in the concentration in the actual streets but also in the sea. Thus by closing the city centre a part of the pollution is transported away from inhabited areas.

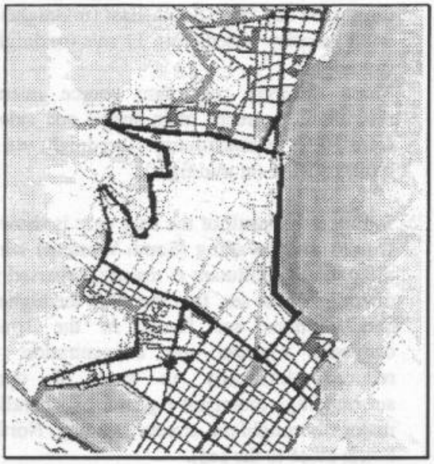

Fig. 6. Calculated concentration distribution for the "Closed Area" case.

The results for the case with low wind is shown in Fig. 7. It is immediately seen that this represents the worst case situation, due to the (nearly) stagnant wind conditions.

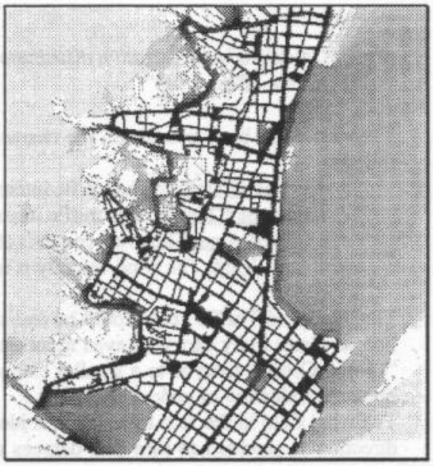

Fig. 7. Calculated concentration distribution for the "Low Wind" case.

For the analysis 5 different preliminary indicators have been constructed:

1. Area High: Area where the (relative) concentration is beyond a high value (0.8).
2. Area Medium: Area where the concentration is beyond a medium value (0.4).
3. Area Low: Area where the concentration is beyond a low value (0.01).
4. Weighted Area: "Area Low" multiplied with concentration.
5. Average concentration: Average (relative) concentration in "Area Low".

The results from the 5 cases are shown in Table 1.

Table 1. Indicator values for the different scenarios examined.

	Base Case	**Reduced Traffic**	**Increased Traffic**	**Closed Area**	**Low Wind**
Area High	0.15 km^2	0.06 km^2	0.44 km^2	0.17 km^2	0.66 km^2
Area Medium.	1.59 km^2	1.19 km^2	1.70 km^2	1.34 km^2	2.11 km^2
Area Low	13.22 km^2	12.39 km^2	13.84 km^2	13.17 km^2	18.93 km^2
Weighed Area	1.34 km^2	1.08 km^2	1.58 km^2	1.35 km^2	2.35 km^2
Average Conc.	0.10	0.09	0.11	0.10	0.12

From the table is seen that all indicators show that the "Low Wind" case is the worst case investigated. The "Area Low" indicator varies only slightly in the four remaining cases. This indicator shows that the area, where the pollutant can be traced, is more or less constant for the same meteorological conditions. However the values of the area indicators changes dramatically when the threshold concentration increases. Thus increases the "Area High" by a factor of three when the traffic increases 30 % and more than a factor 4 due to unfavorable meteorological conditions. The "Weighed Area" is an indicator for the total mass of the pollutant in the solution domain. It correlates rather closely with the "Area Medium" indicator. The "Average Concentration" is an example of an indicator which is (nearly) independent of the scenarios investigated.

The values of the indicators in the two cases "Base Case" and the "Closed Area" are about the same in the Table. Thus, they do not reflect the fact that less inhabitants are exposed to pollution in the latter case. This suggests that indicators based on inhabited areas instead of total areas would be better suited for decision support systems, where health effects has to be considered.

CONCLUSIONS

The results obtained in this preliminary exercise seem to give at least qualitative consistent results. They indicate that a decision support system based on the model concept presented could be an important tool for decision makers involved in urban air pollution management.

However, it should be stressed that the results presented are only preliminary. Until now, they have not been validated against any experimental data. This validation is planned to be performed within the coming six months and will undoubtedly lead to improvements in the physical description of the dispersion process. As indicated above also a more careful selection of scenarios and indicators is needed, and the results need to be integrated in the decision support system. allowing the decision-maker to evaluate them.

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