Multi-objective analysis of ground-level ozone concentration control

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Abstract

To develop sound air quality plans, regional authorities should have instruments that link the complex behaviour of pollutants both in time and space with costs of emission reduction. The problem is particularly important for ground level ozone which forms kilometres away, hours later from the emission of its precursors. To approach this problem, a method (1) to identify local pollutant-precursor models on the basis of results from a large photochemical model (CALGRID), (2) to integrate them in a multi-objective mathematical program, together with an estimate of the emission reduction costs, is suggested. The method has been used to assess action priorities in Lombardy (Northern Italy). This area, characterised by a complex terrain, high urban and industrial emissions and a dense road network is often affected by severe photochemical pollution episodes during summer.

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1. Introduction

Photochemical pollution represents an increasing problem in most urban and industrialized areas in the world. In particular, when meteorological conditions do not provide a sufficient exchange of air masses, ground level concentrations of ozone may reach levels that are considered dangerous for both population and vegetation.

A major task of regulatory agencies is to develop plans to mitigate such heavy pollution episodes and direct their efforts towards a stable solution to this problem. These plans must be formulated in terms of reductions of the emissions of ozone precursors; typically nitrogen oxides (NO\textsubscript{x}) and volatile organic compounds (VOC). In principle, such reductions should be fixed on the basis of a cost-benefit analysis, i.e. minimizing the sum of pollution damages and emission abatement costs.

Since the estimation of pollution damages often proves unfeasible, a more conventional approach is to adopt a cost-effectiveness analysis, i.e. abatement costs are minimized and subject to a constraint representing an acceptable air quality (Schleiniger, 1999; Streets et al., 2001); or air quality and abatement costs are considered separately and a multi-objective optimization problem is formulated (Finzi and Guariso, 1992).

The last approach has already been followed in the literature for the problem of defining ozone precursor emission controls (Schöpp et al., 1999; Finzi and Guariso, 1992) and will be used in this work as well. Such a problem has rarely been tackled in the literature mainly due to the difficulty of including the complex non-linear dynamics of ozone formation within the optimization problem formulation. For this purpose, the source-receptor relationship has been described using ozone isopleths (Flagen and Seinfeld, 1988; Loughlin, 1998) or with reduced form models. The latter ones can in turn be divided into simplified photochemical models, for example, adopting semi empirical relations calibrated with experimental data, as in Venkatram et al. (1994), or using statistical regressions on the results of very complex 3D transport-chemical models (Schöpp et al., 1999; Friedrich and Reis, 2000; Shih et al., 1998). The final multiobjective mathematical problem can then be solved by various techniques, including genetic algorithms, as in Loughlin (1998).

An additional aspect of the problem is the space domain involved. Friedrich and Reis (2000) and Schöpp et al. (1999) solve the problem for Europe assuming uniform reductions in each country and evaluating pollution on a 150 $\times$ 150 km\textsuperscript{2}.
2. Problem formulation

The problem of controlling ground level ozone is formulated in this section as a two-objective mathematical programming problem. The decision variables that will be considered are the reductions of precursor emissions with respect to a reference situation. In principle, each separate emission source can be considered as a decision variable, but, besides being computationally unfeasible, such an approach would be considered politically unacceptable. What a regional authority can do is to actually impose a reduction over a certain area or to a certain emission sector. For instance, it can impose the adoption of a certain abatement technology to power plants or to chemical industries or a certain fuel type to motor vehicles. Because the relocation of large emission sources is considered to be outside the power of the authority, it is natural to assume the existing distribution of activities in a certain sector and consider as decision variables a common percentage of emission reduction for the sector, i.e. the same reduction for all the activities in that sector throughout the region. This approach can be easily adopted since the standard CORINAIR emission inventories (EMEP, 1999) classify all the activities within 11 (macro)-sectors and one can explore all the emission abatement technologies and the related costs for each of them.

Following the approach developed at IIASA (Schöpp et al., 1999), to formulate the problem, we will go through a series of steps that will be described in detail in the following sections. They are:

1. Use of a three-dimensional photochemical model on the domain to compute ozone concentration in the reference case, representing a real emission situation, and in some hypothetical reduction scenario. To implement the model, the region will be subdivided into a number of equal square cells.
2. Definition of a pollution index and identification of a simplified non-dynamic pollution-precursor model that links the pollution index to the precursor emissions for each cell.
3. Identification of cost functions that compute the unit abatement cost in each sector, as a function of abatement level.
4. Determination of the set of non-dominated solutions of the two-objective problem: minimizing the pollution index-minimizing the emission reduction costs, assuming the reduction rates, for each precursor and each sector, as decision variables.

We will use the following notation:

- \( N_i \) and \( V_i \), where index \( s \) refers to the activity sector, will indicate daily regional NO\(_x\) and VOC emissions in the reference case, while \( N_i = (1 - r_i^n)N_i \) and \( V_i = (1 - r_i^n)V_i \) will denote the precursor emissions, when a common reduction factor \( r_i^n \) is applied to all regional activities in sector \( s \) for pollutant \( p \) (\( p = n, v \)); and
- \( N \) and \( V \) are the total emissions, i.e. \( N = \sum_s N_i \) and \( V = \sum_s V_i \);
- \( N(i,j), N(i,j), N(i,j) \) and \( V(i,j), V(i,j), V(i,j) \) will represent the same quantities for cell \( (i,j) \) of the domain;
- \( S_{ij} \) is the neighbor of cell \( (i,j) \), i.e. the set of adjacent cells.

In principle, all emissions vary during the day on an hourly basis, however, since the pattern of daily variation is assumed to be fixed during the week, this time dependency may be disregarded in what follows. On the contrary, it is an essential component of the photochemical model illustrated in Section 2.1.

2.1. Three-dimensional photochemical model

Ground level ozone pollution has been simulated implementing the well-known CALGRID photochemical model (Yamartino et al., 1992) over an area of 240 × 232 km\(^2\) (covering the entire Lombardia region) on which a regular grid with cells of 4 × 4 km\(^2\) (for a total amount of 3480 cells) has been defined. Vertical domain has an extension of 3900 m above ground level and it has been subdivided into 11 levels of growing thickness. Simulations have been performed for a 3 days period (5–7 June 1996)
during which all of Europe has suffered for high ozone concentrations.

The selected episode shows the typical mesoscale meteorological situation that generally induces smog episodes: anticyclonic stable conditions with low speed breeze wind, clear sky and high temperature. Most high-concentrations periods are due to such mesoscale patterns that are quite common in Northern Italy (Louka et al., 2003), so the selected episode can be regarded as a typical ‘critical case’. Consequently, any reduction that will prove effective in such circumstances, will perform equally well for most summer peak episodes.

The base case simulation has been performed feeding CAGRID model with the actual meteorology and emissions, respectively provided by the application of CALMET (Scire et al., 1990) and POEM (Catenacci et al., 1997), but on the basis of an acute episode the choice cannot be defined. All the parameters of these models can be estimated by minimising the squared difference between the model results and the concentrations obtained by using the complete photochemical model on the available data. By performing several simulations with CALGRID, corresponding to arbitrarily chosen emission scenarios, one may produce as much data as needed to reach a sufficient reliability of the estimated parameters.

The computation of such a simulation takes few hours and this explains why CALGRID cannot be directly used within an optimisation procedure that would possibly imply hundreds of model runs.

Keeping the meteorology and border conditions as constant while arbitrarily reducing the emissions of a certain percentage, one may generate a series of alternative scenarios to be used for the calibration of the pollutant-precursor models presented in Section 2.2.

2.2. Pollutant-precursor models

The selection of the air pollution index is greatly restricted in the present case by the availability of ozone values. Obviously, in other studies the adoption of long term exposure indicators, such as AOT40, is possible (Heyes et al., 1997), but on the basis of an acute episode the choice is restricted to short term indicators. The European regulations (EU Directive 96/62/EC, http://europa.eu.int/eur-lex/en/lif/dat/1996/en_396L0062.html) established that the reference value for ground level ozone is the maximum moving average over periods of 8 hours and this index will be used in the following. Clearly, given the role of sunlight in ozone formation, only daily hours are of interest.

Pollutant-precursor models have been defined over the same grid of square cells used by the photochemical model. For each cell, the relationship between emissions and pollution can be approximately expressed as:

\[
I_{ij}(r_{i}^s, r_{i}^v) = a_{ij} \sum_{x,y \in S_i} N(x,y) + b_{ij} \sum_{x,y \in S_i} V(x,y) + c_{ij} \left( \sum_{x,y \in S_i} N(x,y) \right)^2 + d_{ij} \left( \sum_{x,y \in S_i} V(x,y) \right)^2 + e_{ij}
\]

where \(i\) and \(j\) are the cell position indexes; \(I_{ij}(r_{i}^s, r_{i}^v)\) is the air quality index. In this case, it is the maximum value over the entire episode of the 8 h average ozone concentration per cell \((i,j)\), \(N(x,y)\) and \(V(x,y)\) are again the NO\(_x\) and VOC emissions of cell \((x,y)\), and \(a_{ij}, b_{ij}, c_{ij}, d_{ij}, e_{ij}\) are the model parameters.

This simple quadratic model has been selected among several hundreds of different mathematical formulations (using a commercial statistical package), because it turned out to be the best in reproducing CALGRID concentrations (see also par. 3). Moreover, it is based on a simple and understandable parameterisation of the main processes that describe photochemical pollution and it has been used in a former study on Europe (Heyes et al., 1997).

One such model exists for each cell in the computation domain, except for those on the border for which a complete neighbour \(S_{ij}\) cannot be defined. All the parameters of these models can be estimated by minimising the squared difference between the model results and the concentrations obtained by using the complete photochemical model on the available data. By performing several simulations with CALGRID, corresponding to arbitrarily chosen emission scenarios, one may produce as much data as needed to reach a sufficient reliability of the estimated parameters.

It is important to note that such models are not meant to represent a simplified version of the complete CALGRID model. They compute local values of a specific index, instead of the hourly concentration of all the pollutants on the entire domain. However, they proved sufficiently accurate in reproducing the variations of the selected air quality index within a certain range of precursor emission reductions (see par. 3).

2.3. Air quality objective

The air quality objective can be expressed as the minimization of a weighted sum of the damages to population and vegetation. Assuming that the pollution index \(I_{ij}\) is a good indicator of acute pollution effects, it can be multiplied by the densities of population and vegetation to represent the respective damages, i.e.:

\[
\text{min}(\text{Air Pollution}) = \min_r \sum_{i,j} \left[ \alpha p_{ij} I_{ij}(r_{i}^s, r_{i}^v) + (1 - \alpha) v_{ij} I_{ij}(r_{i}^s, r_{i}^v) \right]
\]

where

\[
\alpha \quad \text{is the weight of population versus vegetation impacts;}
\]

\[
p_{ij} \quad \text{is the population density of cell (i,j);}
\]

\[
v_{ij} \quad \text{is a measure of vegetation density in cell (i,j);}
\]

\[
r \quad \text{is the set of decision variables \{r_{i}^s, r_{i}^v\}.}
\]

Pollution effects on vegetation, particularly with regards to ozone, seems to be more dependent upon long term concentrations. In this application (see par. 2.1) air quality has been defined on the basis of a 3 day episode. For this
reason, the effects of reduction policies were evaluated only on population (α = 1). Nevertheless, if in the future a long term simulation is available, other kinds of air quality indexes could be estimated (e.g. AOT40) and the full form of the objective function could be used.

2.4. Cost objective

The cost objective function is formulated as

$$\min(c\text{osts}) = \min \sum_{s=1}^{11} \left( r_s^p \bar{N}_s c^p_s(r_s^p) + r_s^v \bar{V}_s c^v_s(r_s^v) \right)$$

where

$$s = 1, \ldots, 11, \text{ since the CORINAIR classification of all activities in 11 (macro)sectors has been used, and } c^p_s(r_s^p) \text{ is a function giving the unit costs of emission reduction } r_s^p \text{ for sector } s \text{ and pollutant } p, p = n, v, \text{ and } \bar{N}_s(i,j) \text{ and } \bar{V}_s(i,j) \text{ have already been defined as the emissions of sector } s \text{ in the reference case.}$$

Available technologies allow for a maximum emission reduction for each sector and pollutant. This means that a set of constraints

$$0 \leq r_s^p \leq R_s^p \quad s = 1, \ldots, 11 \quad p = n, v$$

must be included in the problem. As it will be explained later in Section 3, on the basis of results of the photochemical model in the case of Lombardy, only VOC emission reductions (i.e. p = v) have been considered. This is why index p is skipped in the following.

2.5. Multi-objective non-linear programming formulation

The complete problem can now be formulated and solved. The two objective problem is expressed as:

$$\min(Air\ Pollution) = \min \sum_{i,j} p_{ij} f_j(r)$$

$$\min(Costs) = \min \sum_{i=1}^{11} r_s^v \bar{V}_s c^v_s(r_s^v)$$

with the constraints:

$$0 \leq r_s^v \leq R_s^v \quad s = 1, \ldots, 11$$

where

$$r_s^v$$ are the decision variables, that is, the VOC emission reduction factors for each sector s;

$$c^v_s(r_s^v)$$ are the unit costs related to the VOC emission reduction for sector s;

$$p_{ij}$$ is the population of cell (i, j);

$$R_s^v$$ is the maximum feasible reduction for sector s.

The problem has been solved by applying the constraints technique (constraining the costs below a parametric value, the other objective is optimised; then the procedure is iterated changing the cost constraint), and each single-objective non linear problem has been solved by applying a conjugate gradient method.

3. The Lombardy region case study

Lombardia Region is a densely inhabited and industrialised area located in the Po Valley (Northern Italy) which is regularly affected by high ozone levels during summer months. CALGRID modelling system has been extensively applied for scientific projects over the Milan metropolitan domain, the major urbanised and industrial area in the Region, to reconstruct intense ozone episodes (Tamponi et al., 1992; Silibello et al., 1998) and to evaluate the environmental impact of emission abatement strategies (Catenacci et al., 1999; Volta and Finzi, 1999). Recent works (Silibello et al., 2000) analyse the chemical regimes, characterising the domain by using the indicator approach (Sillman, 1999). They point out that the region shows a VOC-limited atmospheric chemistry, suggesting that pollution control measures should first aim at a reduction of VOC emissions. Indeed, extensive experiments with CALGRID have demonstrated that a reduction of NOx emissions may even worsen peak ozone concentrations. One such situation is shown in Fig. 1 where the differences of the pollution index between the results of the simplified and the original model is greater than 0.8). On the contrary, the relation is poorly represented by the pollutant-precursor model.
Fig. 1. Differences between pollution indicator values obtained in the base case and with a 35% precursor reduction.

Fig. 2. Pollutant-precursor model performance index.
models in the flat land (south-east) and it is almost non-existent in the Alps region (North).

However, even using the complete CALGRID model, these areas turn out to be almost insensitive to any reasonable reduction of precursor emissions in the domain (see again Fig. 1). They are in fact characterised by lower emissions compared to urban context and their ozone concentrations are mainly due to transport phenomena rather than local production. In other words, they are more affected by the emission field at a larger scale (possibly the whole of Europe), which is represented here by boundary conditions, than from emissions within the domain under study. This explains why the pollution-precursor model, that links the variation of the ozone index only to local emissions, performs poorly in the south-east plain and in the Alps and also means that the situation of these areas cannot be improved by control policies adopted at regional level. Therefore, the optimisation problem has been solved only for the part of the region where the variation of the pollution index is strongly dependent upon reduction of precursor emission and is reliably represented by the simplified models (performance index greater than 0.7, i.e. darker zones of Fig. 2).

4. The emission control variables

As already anticipated, a VOC-limited regime dominates the area. This means that a reduction of NOx cannot improve ozone concentration unless VOC are strongly reduced. This is why only the VOC emission reductions \( r \) are considered as decision variables. They are defined according to the CALGRID system emission pre-processor and the CORINAIR emission classification:

- commercial, institutional and residential combustion plants
- industrial combustion
- production processes
- extraction and distribution of fossil fuels
- solvent use
- road transport
- waste treatment and disposal
- agriculture

Furthermore, the emissions from

- public power, cogeneration and district heating plants
- other mobile sources and machinery
- nature

are supposed to be fixed (they contribution is small and/or there are no plans to act in these sectors).

The sector shares of the total base VOC emission are quoted in Table 1. The Swiss contribution across the border is estimated to about 0.1%.

<table>
<thead>
<tr>
<th>Emission macro-sectors (CORINAIR classification)</th>
<th>% in total VOC emission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public power, cogeneration and district heating plants</td>
<td>0.04</td>
</tr>
<tr>
<td>Commercial, institutional and residential combustion plants</td>
<td>0.49</td>
</tr>
<tr>
<td>Industrial combustion</td>
<td>0.20</td>
</tr>
<tr>
<td>Production processes</td>
<td>2.14</td>
</tr>
<tr>
<td>Extraction and distribution of fossil fuels</td>
<td>4.42</td>
</tr>
<tr>
<td>Solvent use</td>
<td>42.31</td>
</tr>
<tr>
<td>Road transport</td>
<td>38.30</td>
</tr>
<tr>
<td>Other mobile sources and machinery</td>
<td>1.19</td>
</tr>
<tr>
<td>Waste treatment and disposal</td>
<td>10.24</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0.06</td>
</tr>
<tr>
<td>Nature</td>
<td>0.54</td>
</tr>
</tbody>
</table>

The main emission sectors in the domain are the ‘solvent use’, the ‘road transport’ and the ‘waste treatment and disposal’.

5. The emission abatement strategy cost curves

The abatement cost curves were estimated on the basis of a large data set collected for Italy by IIASA (http://www.iiasa.ac.at). The cost of a unit emission reduction, incurred by adopting several technological alternatives for each activity included in each sector, has been assessed. These data, represented by dots in Fig. 3, allow to estimate a rough emission abatement cost function for each sector, fitting the costs and the efficiency of the available technologies. This fitting has been performed only within zero and the maximum possible reduction, with the constraint of producing a monotonically increasing and convex function. As an example, Fig. 3 shows the cost curves estimated for industrial combustion and solvent use sectors. Clearly, a given reduction \( r \) must be interpreted as the implementation of a mix of different technologies (including no changes) distributed in the area, such that their combined effect produces the desired emission at the estimated cost. This assumption may be justified by the very large number of small sources producing emissions in the region, which may be required to adopt different abatement alternatives.

6. Results

The base emission scenario obviously implies no costs and produces a reference air pollution index (its numerical value cannot be easily interpreted, being the sum of the product of the population density times the ozone peak concentration). Instead, if one adopts the best (and more
expensive) reduction technologies in all the sectors considered, the cost is about 1.5 million euro per day with a decrease of the other objective of about 28% with respect to the reference value. This corresponds to a total emission reduction close to 78%. These values are useful to clearly point out the non-linear behaviour of the system and the role played by the population density in the objective function: even a strong reduction of emissions improves the air quality on the more populated areas of the region only moderately, thus the decrease of the pollution index is far from being proportional to such an emission reduction.

These extreme values have no practical meaning, because they represent either the lack of any control action or an excessive burden on the polluters. Furthermore, the maximum reduction case may imply a strong change in the atmospheric chemistry for which CALGRID could not be calibrated. They are useful, however, for they define the so-called Utopia point, i.e. the independent optimal value of the two objectives. This is the point towards which any control policy should aim, but also it represents the reference for judging any policy proposal. For instance, a policy leading to a reduction of the pollution index by 20% should be considered as extremely good, since it covers 71% of the maximum achievable performance (which is a reduction of 28%).

Fig. 3 depicts the set of non-dominated solutions of the two objective problem. Both axes have been rescaled to the maximum feasible variation so that the utopia point lies in the upper left corner. As already pointed out, the most interesting portion is the central part of the curve, for the reason outlined above as well as for the fact that the curvature is stronger, meaning that an improvement in one objective does not imply a strong sacrifice of the other, in the area concerned.

For instance, a solution corresponding to 50% of the maximum air quality improvement, shown by point X in Fig. 4, can be attained with only 20% of the maximum cost (the derivative of the curve is very high in correspondence with low expenses in pollution reduction), while the marginal costs grow with the increase of emission reductions.
The values of the main decision variables that give the optimal solutions just presented are shown in Fig. 5. The sector on which the decision maker has to concentrate are solvent use (n. 6), road transport (n. 7) and waste treatment and disposal (n. 9). The other sectors become of interest only when very strong emission reduction is required. Sectors 6 and 7 alone represent about 78% of the total VOC emissions in the base case, while they are reduced to 41% when the maximum reduction alternative is taken. Around the interesting solutions (again, for instance, 20% of the maximum cost; 50% of the maximum pollution index reduction), the emissions of these sectors should be lowered to about 60% of the base case. The impact of sector 9 is relatively small, but it has few technological alternatives at a convenient (relative to other sectors) cost. This is why one should think to act on this sector even at very low budgets.

Given that the reduction obtainable in waste treatment and disposal is small, it represents 40% of the total emissions in the maximum abatement scenario. This is an indication that more effort should be put in developing new less emitting technologies for waste treatment.

Finally, even in the lowest emission scenario the sectors which have not been considered as decision variables still emit less that 10% of the total.

7. Concluding remarks

Though based on a number of simplifying assumptions, the work has succeeded in pointing out which are the emission sectors that the regional authorities should first take into consideration to reduce ground level ozone concentration with a minimum social cost and how the effects of such reductions would be distributed in the area under study. Furthermore, it showed that a consistent reduction of ozone peaks can be attained in Lombardy with only a fraction (about 20%) of the costs of adopting the best reduction technologies.

Obviously, the availability of a larger number of pollution episodes should allow a more reliable calculation of the expected benefit of alternative decisions, but given the strong differences among the sectors, these appear to be already clear.

A more important development would be to use a similar technique to understand priorities on where reduction should first be actuated or imposed. If one considers as decision variables not only the emission sectors but also the emission positions (all the domain is subdivided in $4 \times 4 \text{ km}^2$ cells) also the areas which have a major impact on the overall pollution index would emerge. However, this would mean solving a problem with a few thousand decision variables, which cannot practically be done without introducing additional simplifications. A more feasible (and realistic) approach would be to introduce separate decision variables for each province (11 areas in the region) and thus determine the best reduction factors for each sector and for each province. It is still unclear, however, if different reduction policies in each of these areas would be acceptable from the political point of view.

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