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Balancing Externalities and Industrial Costs in Air Quality Planning

Claudio Carnevale[a], **Giorgio Guariso**[b], **Enrico Pisoni**[c], **Marialuisa Volta**[a]

[a]*Dept. of Mechanical and Industrial Engineering – University of Brescia, Italy*
[b]*Dept. of Electronics, Information and Bioengineering – Politecnico di Milano, Italy*
(giorgio.guariso@polimi.it)
[c]*European Commission, Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749, I-21027 Ispra (VA), Italy*

Abstract: When adopting regional plans aimed at improving air quality, environmental authorities are often faced with the relevant costs that the adoption of abatement measures implies. On the other hand, scientific literature has well documented damages due to air pollution impact on human health and ecosystems. This paper proposes a tool that allows balancing these two viewpoints by defining the efficient set of measures in a multi-objective perspective. Despite both external (health related) and internal (industrial/emission abatement related) costs can be measured in the same unit, namely money, it appears unacceptable to add them together as in a cost-benefit analysis, since they pertain to quite different social groups. The tool proposed in this paper can thus be seen as a support to actual decision makers and allows them to compare in a ponderable way the pros and cons of any abatement policy. This contrasts what normally happens when air quality health impacts are simply defined as the satisfaction of a constraint at few specific points in space (coincident with the presence of measurement gauges). Indeed, both population and ecosystems are distributed in a non-uniform way on a territory and thus sparse point measurements of pollutant concentrations or other related air quality indicators may be only loosely related with the real impacts of air quality. An application of the tool to a European region (Lombardy, Italy) is presented with particular reference to PM10 and Ozone pollution problems. These are particularly difficult to cope with, since these pollutants are mainly formed in the atmosphere (secondary pollutants) and thus their concentration depends on chemical-physical processes involving in different way on one side the emission of precursors and, on the other, the local meteorological conditions.

Keywords: secondary pollutant; multi-objective optimization; cost-benefit analysis.

1. INTRODUCTION

The design and implementation of regional and local air quality plans must tackle relevant challenges due to a series of institutional, economic, and physical factors. From the institutional viewpoint, the problems are due to the limited power normally assigned to local government and environmental agencies. They can enforce some regulations, forbid certain emissions, but have to act within the limits imposed by national and international rules. Additionally, local air quality plans may be very costly and thus it is important that their effects can be compared with the related effort, that the burden is equally distributed among citizens and activities, and the budget available is allocated among possible alternative reduction measures in the most effective way. Last, but not least the problem is extremely complex for its physical features. The pollution in a region may largely depend on the emissions of neighboring areas, outside the control of local authorities. Many important pollutants such as tropospheric ozone and particulate matter are largely (if not completely) secondary ones, meaning that they are not directly emitted and form in the atmosphere following a number of physical and chemical reactions among precursor emissions sometimes kilometers away from the emission sources. Actions taken to reduce the emissions of a certain precursor to achieve some improvement of a certain secondary pollutant may adversely affect the dynamics of another pollutant.

Several methods and tools have been proposed to develop decision support systems that may assist in analyzing and approaching in a systematic and transparent way this complex decision process (e.g. Holland et al., 2008, Amann et al., 2013). The most comprehensive among them integrate the relationship between emissions and pollutant concentration (normally represented by a chemical transport model or some suitable approximation of it) with the economic evaluation of emission reduction costs and some air quality indicator summarizing the effects of air pollution on the local environment (Wagner et al., 2013).

The present paper rapidly reviews the experience of the authors in the last years (Carnevale et al., 2011; 2012; 2014) and proposes a method to disentangle situations in which alternative reduction measures are conflicting by resorting to some estimation of external costs (namely, those incurred by the population and the environment due to air pollution). Some preliminary results of applying this method to an Italian region, Lombardy, are also given.

2. THE MULTI-POLLUTANT PROBLEM

If a local authority can impose the adoption of some specific emission reduction technologies X (clearly, the set of these technologies is determined by the type of activities and industrial processes taking place in the region as well as by the actions that may be actually undertaken), the overall problem can be formulated as a multi-objective, generally nonlinear, programming problem (see Carnevale et al., 2012, for details), where the regional air quality situation is represented by a limited set of aggregated values, called here Pollution Indices (PIs). The overall problem can thus be formalized as:

$$\min_{X} [P_1(E(X))...P_h(E(X))...P_N(E(X))] \qquad (1)$$

$$C(E(X)) \leq B \qquad (2)$$

$$X \geq 0 \qquad (3)$$

where:

$E(X)$ represents the precursor emissions, as a function of the set of decision variables (emission control measures) X;

$P_h(E(X))$, $h = 1,..., N$ are suitable air pollution indices related to different pollutants;

$C(E(X))$ represents the implementation costs of emission reduction measures;

B is the (limited) amount of funds that the local government estimates that can be invested in the improvement of air quality. It is important to understand that this is not the actual budget of the plan since a part of the costs will be bared by the society (firms, industries, population) and not directly by the decision agency.

Various Pollution Indices (PIs) can be selected. In some regions, for instance, the concerns mainly relate to O_3, and PM (see the following example on Lombardy), while in others the connection between PM and NO_2 may be more important (Carnevale et al. 2014). Additionally, such pollution indices may be relevant only in a specific season (for instance, in Europe high PM is mainly a winter condition, ozone for its own dynamics is only a summer problem) while other like NO_2 may refer to an entire year. In all cases, they combine point hourly or daily concentration values (those normally corresponding to actual measurements or to the output of a CTM - Chemical Transport Model) into some indicator, usually aggregated in time (one or more years or one or more seasons) and space. The definition of such an indicator is thus relatively critical. The spatial integration necessarily assumes that the territory under consideration can be subdivided into a number of homogeneous grid cells. The aggregation then may vary from a simple average over all cells belonging to the area of interest, to a weighted average (for instance, using population density), or to a subset of cells in which exceedance of a concentration threshold is reached.

Whatever the case, a key point for the solution of the above problem is the availability of a fast performing model to compute PIs as a function of current emissions. Current CTMs like Chimère (Bessagnet et al., 2004) or CAMx (Tesche et al., 2006), are far too computationally heavy to be used thousands of times within the optimization procedure. For this reason, a suitable surrogate model of limited complexity must necessarily be employed, after training it on the specific territory so that it can replicate as close as possible the impact of emission variations (with the assumed meteorology) on the indices. Possible surrogate models are linear (as in Amann et al., 2011) or nonlinear (as in Carnevale et al., 2014).

In particular, in the following example as well as in other cases, the authors have used artificial neural networks (ANNs) to approximate the results of chemical-transport models. The combined use of ANNs and specific emission aggregations (to retain only the key emission information affecting air pollution) allows for the identification of surrogate models that are highly flexible, fast in execution, and, more important, that have the capability to reproduce the CTM behavior over a large range of input conditions, requiring a limited number of (well designed) CTM simulations.

A specific feature of the approach developed by the authors is that such ANNs are not trained to replicate concentration values in each cell of the domain at each time step (which do not enter explicitly into the optimization procedure), but rather to compute time aggregated values necessary to compute the PIs, that are those needed for the solution of the problem. Additionally, these integral values show much less variation, thus can be replicated more accurately.

3. EXTERNAL COSTS OF AIR POLLUTION

Several studies have tried in the recent years to quantitatively estimate the impact of air pollution on human health and ecosystems in monetary terms (e.g. Amann et al., 2011, or the EU project METHODEX – "Methods and data on environmental and health externalities: harmonising and sharing of operational estimates"). Most of them adopted the methodology first introduced in Europe by the EU ExternE approach (Bickel and Friedrich, 2005). This approach is linear in the pollution indices and thus assumes the possibility of adding the effects of different pollutants. More sophisticated methods are presently under study, because it is quite obvious that this additive assumption may be reasonable only for very small variations around the current situation (around which impact factors are estimated). ExternE method first transforms the PI in each cell (for instance, the average yearly PM10 concentration) into an indicator of human morbidity, or mortality, or ecosystem damage (for instance, crop reduction for ozone impact) and then transforms such an indicator into an amount of money, by simply multiplying it by a unit cost. The estimation of this cost is in itself a quite complex economic problem: it can be evaluated using techniques such as willingness-to-pay or hedonic pricing value, but since it is normally estimated at national level will not be further examined in this context.

The factors more related to the specific territory are accounted for with different formulas. For instance, a generic health indicator h_i is computed as

$$h_i = \sum_{c=1}^{C} \sum_{g=1}^{G} \sum_{x,y} f_{icg} PI(x,y) POP_g^c(x,y) \tag{4}$$

where

c is a cohort index (typically the population is split into age classes of five years each);

g is a group index (the population can be further partitioned, for instance, into asthmatic and normal);

x,y are the coordinates of the cell under consideration;

f_{ics} is the incidence per unit of PI of the specific health problem i in class c of group g;

PI(x,y) is the pollution index in cell x,y;

$POP_s^c(x,y)$ is the population cohort and group affected.

The estimation of this last value is also problematic since normally only the resident population in cell (x,y) is considered, but often, if cells are limited to some square kilometers, people may live in one cell, but spend several hours a day in another with a different pollution. Once the value of h_i is computed, its overall monetary value is obtained by simple multiplication for its unit value.

For instance, the computation of external costs related to mortality (caused by long term PM10 exposure) has been implemented in Carnevale et al. (2011) using the number of Years Of Lost Life (YOLL), each of which was evaluated at 50,000 euros. Similar estimations are available also for computing the air pollutants deposition impacts on environment/agricultural components, as i.e. considering crop yields reduction or water bodies acidification/eutrophication.

4. RESULTS AND DISCUSSION

The approach presented in Section 2 has been applied to the air quality plan of the Lombardy region in Northern Italy. The southern part of the region lies in the centre of the Padana plain, the most productive area in Italy for both industry and agriculture, while the northern part comprises a central segment of the Alps. Exactly for these characteristics, the region is often subject to high pollution episodes for both PM and Ozone.

In the following application, at first, a multi-objective programming problem has been solved using yearly average PM2.5 concentration as PI for particulate matter and SOMO35 (sum of the maximum daily 8-hour running mean concentrations, for the part greater than 70 µg/m^3, i.e. 35 parts per billion) as PI for Ozone.

The results are shown in figure 1 as a function of the estimated yearly cost of the adoption of the optimal set of cost-effective reduction technologies. It is important to note, that those considered are end-of-pipe technologies, which means those that can be adopted to reduce emissions without modifying the correspondent activity level. This means that adoption of cars and trucks of a high EURO standard falls in this category (i.e., to subsidize a “scrappage scheme”, to locally boost the diffusion of high EURO standard vehicles), while the limitation of traffic in certain areas, as the city centers, does not belong to it, since it implies a significant change of traffic conditions.

The dot at the right in figure 1 represents the so-called “Current Legislation” conditions (CLE), which is the result of the straightforward application of existing norms. The curves represent the efficient compromises between the two PIs (Pareto frontiers) and are characterized by different levels of investment (in M€ per year) in reduction technologies above those imposed by CLE.

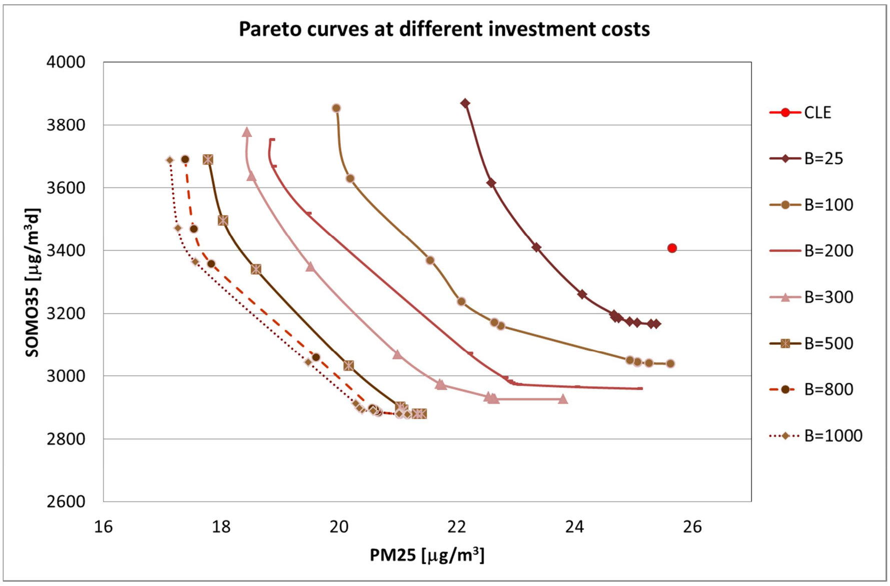

Figure 1. Trade-offs between pollution indices of PM and Ozone in Lombardy.

It clearly appears that more investments may correspond to a reduction of both PIs, but that their effectiveness decreases when approaching a reduction limit. Indeed, even with very high investments, both PIs cannot be reduced to 0, and for instance an average of 17 µg/m^3 of PM2.5 concentration seems insuperable. This is on one side due to the impossibility of existing end-of-pipe technologies to decrease emissions below a certain level and, on the other side, to the fact that a relevant portion of PM concentration in Lombardy is due to the emissions of surrounding areas that, in this exercise, are not subject to any reduction below CLE.

The figure shows that with an investment of 200 M€/year both PIs can be reduced by more than 10% and with 500 M€/year by almost 20%. However, it also shows that there are indeed conflicts between the PM and O_3 and investing all in reducing one of the two may worsen the other.

Once these PIs, that are required by current regulations, have been computed, one can concentrate on one of the curves, say for instance that corresponding to an investment beyond CLE of 200 M€/year and compute the related external costs. It is worth noticing that, while industrial costs are constant along a curve, external costs vary depending on the combination of PIs to which they refer. The minimum of the external cost function may suggest the best selection of actions for a given level of investment.

External costs are useful also because they allow a different perspective on the spatial distribution of pollutants. For instance, relative high ozone values that are found in the northern part of the region traduce in only a small cost since agriculture is not very active at those high elevations. On the contrary, average PM concentrations in some areas in the central part of the region imply relevant health problems because of the high population density. Figure 2 shows for instance the differences in the distribution of estimated reduction of PM costs (background series) in comparison to concentration reduction (foreground series). These values were computed mapping cell concentrations onto municipalities (census data are available only at that level) and then aggregating into provinces. Since the approach used for external costs is linear, such spatial distribution does not change for a uniform increase or decrease of PI values over the region.

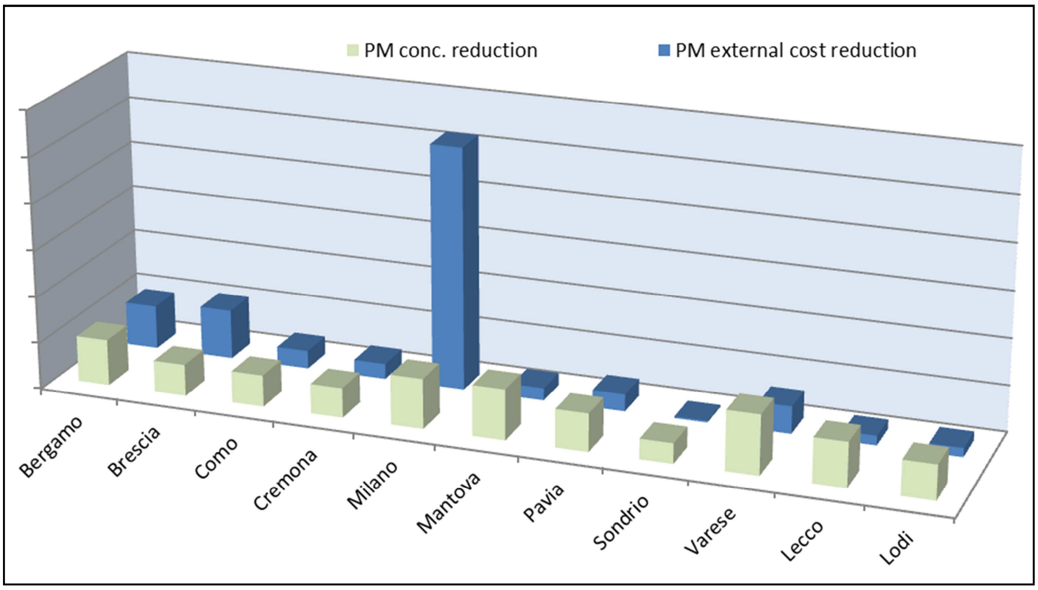

Figure 2. Spatial distribution of external costs of PM pollution, aggregating the results at the department (province) level.

5. CONCLUDING REMARKS

The methodology presented in this paper to support regional and local air quality plans is made of two steps: at first, it solves a multi-objective problem having as decision variables the degree of utilization of abatement technologies and as objective a vector of pollution indices, normally defined by legislation (such a problem can be solved for different levels of investment in emission reduction measures). Second, it evaluates the external costs (pollution damages) related to a set of measures that have the same investment costs, but different (and sometimes conflicting) effects on the PIs considered. The minimum of the external cost may constitute a useful indication of the mix of reduction measures to adopt.

There are several reasons for not summing up investment and external costs and formulate the problem as a traditional cost-benefit analysis. External costs appear in most studies to be at least one order of magnitude larger than industrial ones. So if one takes a sum of the two the optimal solution would go in the direction of minimizing almost only external costs, with little attention to industrial ones. Second, the two costs differ substantially in their timing (investment are to be done rapidly, while external costs also represent effects that can materialize in a distant future) and in the social component that has to bear them. Investment costs normally refer to industry, traffic, heating; while external costs are “paid” by population and ecosystems. Finally, external costs do not represent for many aspects a real flow of money. Even if something can be quantified by looking at the cost of the healthcare system or to that of reduced activity days, most of them represent a decrease of life quality and thus, though important, is not actually paid.

The results of the integrated modeling approach presented in this paper is affected by uncertainties on different issues. These uncertainties (even if not shown here) should be carefully considered to demonstrate the robustness and usability of the proposed solutions. More in detail, uncertainties should be analyzed in terms of input data (i.e. emission inventories, meteorology, etc…) and of modeling approach (uncertainty related to the CTM, to its approximation through the surrogate models and in the optimization procedure). These issues are under consideration as integration of the present work.

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