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Incremental Selection of Regional Air Quality Measures

C. Carnevale * G. Guariso** F. Ferrari*** G. Maffeis*** E. Turrini* M.L. Volta*

** Department of Mechanical and Industrial Engineering, Environmental sustainability Lab (B+ Labnet) University of Brescia, 25123 Brescia, Italy (e-mail: marialuisa.volta@unibs.it)*
***Dept. Electronics, Information, and Bioengineering, Politecnico di Milano, 20133 Milan Italy (Tel: +39 02 2399-3559; e-mail: giorgio.guariso@polimi.it).*
****TerrAria s.r.l., 20125 Milan, Italy (e-mail: g.maffeis@terraria.com)*

Abstract: To comply with EU regulations, local environmental authorities of the regions where the mandatory air quality limits are not met must develop suitable emission reduction plans. These normally represent a compromise among what is economically feasible, what is politically acceptable, and what can provide measurable benefits. As a consequence, they include a large number of different abatement measures pertaining to a wide variety of fields (transport, building, agriculture…), the total effect of which is different from the simple sum of the individual outcome. We illustrate how such a problem has been tackled in an Italian region, supporting the analysis through an integrated modelling tool.

Keywords: Integrated modelling, air quality planning, scenario analysis, decision support.

1. INTRODUCTION

Planning for air quality improvement is typically a task that local environmental authorities have to carry out within the framework set by national norms and international agreements. Two main reasons justify the relevant role played by local decision makers. On the one side, the effects of pollutant emissions do not produce perceivable impacts at more than hundred kilometres from the source and these impacts are strongly dependent on the specific meteorological conditions of the area. On the other side, abatement measures of polluting emissions may be correctly planned only locally, where the characteristics and composition of the emission sources is known. Each territory is indeed specific for area and location of urban centres, for main traffic routes, agricultural and industrial activities. This means that reducing the emissions requires specific knowledge of emission sources and that different measures can be effectively adopted in different context. These considerations explain why the recent years have seen the development of many city/local/regional (meaning related to areas of the order of some hundreds to tens of thousands square kilometres) air quality plans. This is also in line with EU rules (specifically, the Air Quality Directive) that require the administrative structures of zones and agglomerat5ions with low air quality values to develop their own improvement plans.

In the recent years, these plans have been developed using different approaches (Guariso and Volta, 2017, Thunis et al. 2016) and focalizing on different aspects, depending on the specific characteristics of the relevant territory. Most of the European plans recently catalogued by the EU Appraisal project (www.appraisal-fp7.eu) adopt a chemical and transport air quality model to test the effects of different actions on the emission sources. Few plans also evaluate the impacts of pollution on the health of the resident population, but almost none tried to compare the cost of adopting a set of abatement measures with the corresponding benefits in terms of reduced health impacts and energy consumption.

The types of measures adopted in each plan can be numerous, they can be applied to different sectors, impact on different pollutants, and their deployments normally cover a period a several years. The problem of determining the best scheduling for measure adoption is difficult and may lead to intractable combinatorial formulations. Indeed, it has been dealt with only rarely in the scientific literature (see: Shih et al., 1998, for an exception). It becomes even more complex if one considers the trade-off between different pollutants and the necessity of balancing the resources dedicated to each (Carnevale et al., 2014a; 2014b).

An appealing alternative to a detailed mathematical formulation is thus the availability of a user-friendly GIS based tool that can rapidly evaluate impacts and costs of a specific action or set of actions in a specific territory. This allows decision makers to easily understand which are the pros and cons of each set of measures and thus concentrate first on the most effective ones. It is in fact important to underline that the overall effect of a set of abatement actions is not the sum of the effect of each separate measure, if we deal with secondary pollutants such as PM10, NO_2 and Ozone. This is due to the nonlinear dynamics of secondary atmospheric pollution that can sometime generate counterintuitive effects.

This paper reviews some of the typical actions foreseen by one such plans, that of Lombardy region, a highly polluted area in Northern Italy, and shows how an integrated modelling software tool, RIAT+ (Carnevale et al., 2012; Carnevale et al., 2014a) has been used to systematically evaluate costs and benefits of the proposed actions.

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The paper is organized as follows. The next section illustrates the main feature of the Lombardy plan. Section 3 explains the method adopted for the overall evaluation process and briefly summarizes the characteristics of the software tool adopted for the evaluation of each abatement measure, while the following sections shows and comments the results obtained.

2. THE AIR QUALITY PLAN OF LOMBARDY REGION

Formally approved in September 2013 (Regione Lombardia, 2013) the plan (PRIA) consists in a large set of emission reduction measures and foresees the evolution of regional emissions till 2020. The 66 measures to be first undertaken are subdivided in:

• 26 concerning road transport and mobility;

• 27 concerning point emissions and efficient energy uses;

• 13 concerning agriculture and forestry.

In economic terms, the plan takes into account all the infrastructures already under construction with some impacts on the emission of air pollutants, and particularly those related to road transport and mobility, for a total investment close to three billion euros until 2020.

To assist in defining the most effective ones, which can help in determining the degree of priority for the implementation of these measures, we implemented a methodology that consists of three main steps:

- Measure selection
- Emission evaluation
- Impact computation

3. THE EVALUATION APPROACH

To understand how the system works, it is necessary to first explain how emissions and their reduction can be computed.

3.1 Emission evaluation

The base for the definition of an emission field is the knowledge of the spatial distribution of the polluting activities of the territory. This means that a detailed inventory of industries, buildings, roads, airports and all other possible sources must be available, together with the information about the type and quantity of pollutant they emit. Such information is available for Lombardy in the official regional databases: the INEMAR emission inventory (*www.inemar.eu*). Other useful information can be found in the national statistical census (*dati.istat.it*), in the GAINS database (gains.iiasa.ac.at/models/) and many others public databases. It is evident that this type of information lends itself immediately to a geographical presentation and thus a GIS-based tool is a natural and user-friendly environment to work with.

In a unit portion x,y,z of the regional domain (usually, assumed to be a square cell), the impact of a given set of measures $\underline{u}$ that acts on the emission E_p of pollutant p can be formally expressed in the following way:

$$E_p(x,y,z) = \sum_i A_i(x,y,z,\underline{u})ef_{ip}(1-r_{ip}(\underline{u})) \qquad (1)$$

Where

- A_i is some measure of the activity type i going on in point x,y,x of the territory (normally evaluated in terms of energy used).
- ef_{ip} is the "unabated" emission factor of pollutant p by activity i, i.e. the amount of pollutant emitted by a unit activity at time of adoption of the plan prior to the deployment of any additional abatement action.
- $r_{ip}(\underline{u})$ is the fraction of emission reduced by actuating decision $\underline{u}$ on the i-th activity.

The last term can again be seen as the product of two factors: a "reduction efficiency" (the fraction of abated emission of the specific pollutant), that is a characteristic of the technology adopted, and an "application rate", that represents the degree of adoption of the measure in the i-th activity (independent from the pollutant), and thus constitutes the actual decision. Thus, for instance, if a given technology reduces the emission by 50% and is adopted by 50% of the emitters belonging to a certain sector of activity in a given portion of the domain, the emission of that pollutant is reduced by 25% in that area. Being the two factors just fractions, $r_{ip}(u)$ is always smaller than 1. This also means that r_{ip} varies between a minimum value (zero if a technology is not adopted at all) and a maximum value, corresponding to the reduction efficiency, when 100% of the i-th activity in (x,y) applies the measure.

The x and y coordinates in this study represent the indexes of the horizontal position of the domain cell we are considering, while z is discretized into two values: low and high emissions. The first typically refers to diffused emissions, like traffic and domestic heating, while the second is only related to high stacks, such as those of large industrial or power plants.

Following the definition in (1), the abatement measures in an air quality plan can be classified as:

- **End-of-pipe** (also called "technical") measures, that decrease the emission of pollutant with only a negligible decrease of the energy corresponding to that activity, i.e. they simply increase the value of r_{ip} when a larger portion of activity i adopts the technology.

- **Non-technical measures** (also called "efficiency" measures) that modify some emitting activities by reducing energy consumption through a change in production processes or production values. Also changes in the attitude or behavior of the citizens belong to this category. For instance, a shift toward active mobility, like biking, represents a reduction of the energy used in car transport. They are represented by the components of the decision vector u impacting on the A_i values.

- **Scenario measures** do not have a graduality of application, so, for these measures, emissions are either zero or fixed. Examples of such measures may be the closing of a certain activity, or its transfer to a new position. These decisions may also be part of u.

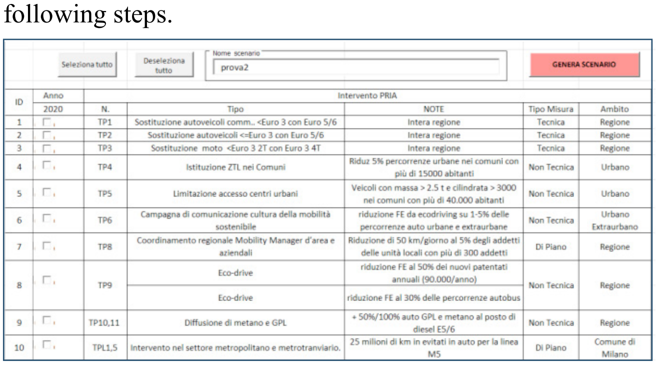
Although this classification is commonly adopted (e.g. in the widely used GAINS model, see Amann, 2011) it is not unambiguous. The substitution of older EURO vehicles with newer ones is often considered a technical measure even if it may involve a higher efficiency and reduced fuel consumption.

Another important characteristic of the decision vector *u* is the territorial extension it concerns. While in principle one may think that a specific set of measures can be defined for each cell (*x,y*), this is not feasible in practice (and it may also be politically unacceptable) and a certain aggregation of cells with similar characteristics or belonging to the same administrative unit must be defined (they represent the so-called *policy application domain*). For instance, a measure concerning domestic heating applies mainly to urban cells, while a measure concerning agriculture only applies to the countryside, and a measure concerning vehicle emissions to wherever there are roads. Clearly, adopting a specific, limited, policy application domain for a certain measure only reduces emissions in that portion of territory, but has normally effects in a much larger domain, where it may reduce concentration and impacts.

3.2 Measure selection

The set of measures included in the plan, may be catalogued in many different ways, according to the emission sector they address, the part of the territory they involve, the investment they require. Each is described in detail in the plan with the emission reductions they imply. For end-of-pipe measures, given that the reduction efficiency of each technology is known, it is easy to determine the consequent application rate. For other measures, a suitable reduction of the activity is assumed. Regional authorities are interested in evaluating the effectiveness of all measures, separately or in groups.

For this purpose, we developed a simple menu interface (partially shown in Fig. 1) that allows the definition of a specific scenario through the selection of the interesting measures. Such a choice is then translated into records that, for all the activities, store the application rate of each reduction measure in a simple text file to be used in the following steps.


Seleziona tutto | Deseleziona tutto | Nome scenario: prova2 | GENERA SCENARIO

ID	Anno 2020	Intervento PRIA N.	Tipo	NOTE	Tipo Misura	Ambito
1	☐	TP1	Sostituzione autoveicoli comm.. <Euro 3 con Euro 5/6	Intera regione	Tecnica	Regione
2	☐	TP2	Sostituzione autoveicoli <=Euro 3 con Euro 5/6	Intera regione	Tecnica	Regione
3	☐	TP3	Sostituzione moto <Euro 3 2T con Euro 3 4T	Intera regione	Tecnica	Regione
4	☐	TP4	Istituzione ZTL nei Comuni	Riduz 5% percorrenze urbane nei comuni con più di 15000 abitanti	Non Tecnica	Urbano
5	☐	TP5	Limitazione accesso centri urbani	Veicoli con massa > 2.5 t e cilindrata > 3000 nei comuni con più di 40.000 abitanti	Non Tecnica	Urbano
6	☐	TP6	Campagna di comunicazione cultura della mobilità sostenibile	riduzione FE da ecodriving su 1-5% delle percorrenze auto urbane e extraurbane	Non Tecnica	Urbano Extraurbano
7	☐	TP8	Coordinamento regionale Mobility Manager d'area e aziendali	Riduzione di 50 km/giorno al 5% degli addetti delle unità locali con più di 300 addetti	Di Piano	Regione
8	☐	TP9	Eco-drive	riduzione FE al 50% dei nuovi patentati annuali (90.000/anno)	Non Tecnica	Regione
			Eco-drive	riduzione FE al 30% delle percorrenze autobus		
9	☐	TP10,11	Diffusione di metano e GPL	+ 50%/100% auto GPL e metano al posto di diesel E5/6	Non Tecnica	Regione
10	☐	TPL1,5	Intervento nel settore metropolitano e metrotranviario.	25 milioni di km in evitati in auto per la linea M5	Di Piano	Comune di Milano

Fig. 1. Sample measure selection menu.

For each measure, the menu specifies its definition, the activities involved, the policy application domain and the classification according to the three categories defined above. Whatever the selected combination of measures, the emission reduction due to end-of-pipe actions must remain in the range between what imposed by the legislation in force, the so-called CLE (Current Legislation) and the Maximum Feasible Reduction (MFR) due to the highest possible diffusion of the technology. For other measures, such a limit does not exist and they can all be applied. Presently, the system sees all measures as separate and thus there is no possibility of improving the emission technology and reduce the energy use on the same activity in the same location, neither this was envisaged in the actual plan.

3.3 Impact computation

To actually support the decisions about which measure or set of measures should be first undertaken, the decision support tool has to be able to show the consequences of each choice within seconds. So, while in principle, one can run each time a complete Chemical-Transport Model (CTM), as done during the development of the plan, we turned to a different approach based on the use of surrogate models (Carnevale et al., 2012).

The procedure followed is rather simple.

A limited number (14 in the case at hand) of runs of a full CTM, TCAM (Carnevale et al. 2008) in the present case, is computed, spanning regularly the range of plausible emission reductions for each pollutant.

The structure of a “local” artificial neural network (ANN) is defined in such a way that it can use local information (e.g. precursor emission in the range of few tens kilometres) to compute some specific indicator of the overall air quality (i.e. not all the information provided by the CTM, but only some aggregated value, such as the average annual value in a cell).

The ANN is trained in order to replicate the CTM results in terms of quality indicator in the area and range of values of interest.

The high speed of scenario computation obtained by this approach is due to the ability of the surrogate model to embed the specific condition of the domain under consideration. For instance, there is no explicit definition of meteorology, since the specific meteorology of the region is used within the CTM, and the surrogate model assumes it as fixed. The main limitation of the approach, on the contrary, is that it is necessary to select, at the very beginning of the procedure, which are the relevant air quality indicators that one wants to consider and a specific ANN must be trained for each selected one. We developed for instance, ANNs to compute average annual PM10 concentration, Ozone AOT40 and SOMO35 (see figure 2) and other aggregate values. Spatial averages over the region can then be obtained using the values of these indicators in each cell. Other indicators, strongly linked to these, can also be derived. For instance for PM10, the number of exceedances of the daily average concentration threshold in one station is closely correlated with the average annual concentration in that point and thus can be derived from the latter with a good approximation.

The RIAT+ system, developed in the LIFE project OPERA (www.operatool.eu), implements the above procedure, runs as a stand-alone desktop application downloadable from www.riatplus.eu. The package is distributed with a personal, non-exclusive and royalty-free license and has been applied in various regions, such as Emilia-Romagna, Alsace

(Carnevale et al., 2014), Porto and Brussels (Miranda et al., 2016).

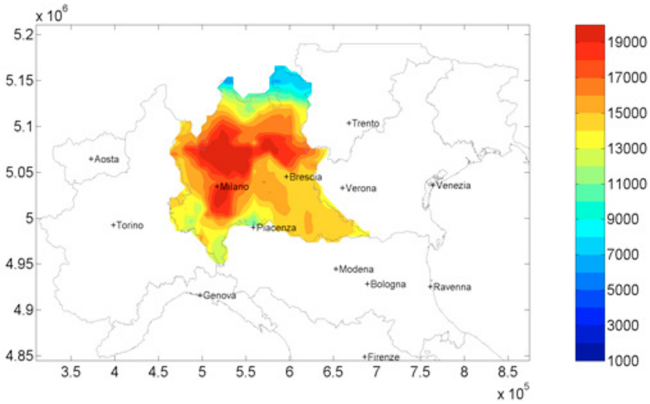


Fig. 2. SOMO35 spatial distribution in $\mu g/m^3*d$ corresponding to the full application of the PRIA plan.

4. ANALYSYS OF THE RESULTS

The results of the study can be read under many different perspectives. Some are closely linked to the situation of the Lombardy region, some others seem to be quite general and thus applicable to other contexts and plans.

Looking specifically to individual measure, the substitution of commercial vehicles with emission standards lower than EURO 3 with EURO 6 vehicles (17 different types of vehicles) would mean substituting cars travelling about 4 billion kilometres for a total estimated cost 5.65 M€, and an emission reduction of 234 tons of PM10, 6385 of NOx, and 433 of VOC. This means a peak reduction of annual average PM10 (primary and secondary) concentrations in the main urban centres of about 1 $\mu g/m^3$ or around 6% with respect to CLE 2020.

The detailed heat accounting for all buildings, an efficiency measure, which again has the largest impact in urban areas, is planned to reduce energy consumption by some 46 million GJ with an annual cost of 39 M€ (being an investment, it has been actualized over a horizon of 15 year at a 5% rate). The adoption of this measure would mean a reduction of 39 tons of PM10, 2700 of NOx, and 255 of VOC. Again, since these heating emissions are at low level and where the population lives, even a relative small reduction is important. Indeed the average NOx reduction over the region is around 4%, but it reaches 15% in the most polluted towns.

As an example of a scenario measure, the building of the new metro line in Milan entails an annual cost of 3.96 M€ (discounted over 25 years at 5%) and is planned to determine a reduction of 25 million kilometres per year otherwise driven by car. This means a reduction of gasoline and diesel car emissions of 1 ton of PM10, 9 of NOx, 2 of VOC. These emission reductions have a negligible impact (of the order of 0.02%) on air quality and thus do not have perceivable effects on the population health. This can be easily understood if one considers that the car mileage in Lombardy is about three order of magnitude larger than the foreseen reduction and traffic is only a component, even if large, of the regional emission field.

5. DISCUSSION AND UNCERTAINTY

Under a more general viewpoint, the study shows that the possibility of important changes in the air quality is quite limited when the policy application domain is limited to a single region within a large airshed as the Padana plain. The CTM runs used for calibration indeed assume that nothing happens in the adjacent region and so the concentration of the border cells remains constant. This is strong constraint in the dynamics of air pollution that prevents average changes in the region to exceed few percent. For instance, even a full implementation of the current regional plan would decrease 2020 average PM10 concentration of only 1.3% with respect to CLE. A first analysis of what can happen if the surrounding regions join the reduction effort shows that this percentage can be at least doubled. In some areas of the domain, such as large cities, the decrease is larger, with a consequent larger impact on the population. For instance, mean annual concentrations of NOx may reach a 22% reductions in large urban centres compared to a regional average of 16.5%.

This takes us to the second important point. Average concentration values over non uniform domains may not be a good representation of the impact of a given measure. A decrease of PM10 average where the population is denser represents a larger effect on public health, same as a decrease of AOT40 in agricultural areas may beneficially impact on agriculture. A geographical presentation is thus essential to understand the complex pattern of pollution distribution.

Third, each measure has an associated implementation cost which is accounted for in the system and has been taken from the GAINS database or from a number of other studies. Such costs are however fixed and thus assume that, whatever measures are implemented, the market will not be changed. For instance, the assumption is that, even if the plan foresees a large adoption of PV panels for power production, their price will remain constant. An extensive sensitivity analysis, not reported here, has been performed to understand how possible price variations may impact on the definition of priority measures. However, price oscillations within reasonable ranges (no strong variations are expected within 2020) have not altered these general conclusions.

Finally, the costs are generally expressed as an annual average fraction on the useful life of the measures, that require a. In general, there will be a period in which investments are made with a negative cash flow, followed by a period of useful life (15-20 years for most of the considered measures) in which the benefits may prevail resetting the deficit (in 5-10 years in most cases). Such benefits may be measured both in terms of internal (energy reduction) and external (health improvement) reduced costs. In the end, positive cash flows will possibly be obtained until the end of useful lives.

6. CONCLUSIONS

Grouping the measures in specific sectors, one may reach some conclusions that can possibly be applied to other cases.

Electric energy measures are the most expensive (e.g. the installation of PV panels) and they do significantly improve air quality. This because the production of electricity occurs in plants with high stacks, generally far from urban centres with strictly controlled emissions. So, an emission reduction from these sources does not lead to significant impacts. The reverse is true for thermal energy, since it can be produced with sustainable technologies and can replace low level emissions in urban centres with a perceivable impact on concentration values.

The measures on private transport show a high impact on the improvement of air quality. The conversion of vehicles to methane and LPG (or electric) seems the measure giving the highest return in term of air quality per unit investment. On the contrary, the impact of changes in public transportation is limited due to the small emission of this sector in comparison to those of private traffic.

It is important to note that the concentration field obtained by the joint adoption of many different measures is in general not the sum of what would be obtained individually considering each measure. This is due to the presence of non-linearity in secondary pollutants dynamics and becomes particularly evident when dealing for instance with Ozone, that is a completely secondary pollutant.

Altogether, given the complexity of the decision problem faced by local environmental authorities, the approach presented here has proven a useful tool in allowing a fast screening of the alternatives and thus a selection of those to implement with the highest priority.

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