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A predictive control approach for air quality management

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Abstract: The control of critical pollutant events has become one of the most relevant problems that the Local Authorities need to manage, in order to limit population exposure to high pollutant levels. The problem of the selection of suitable short terms plans allowing to maintain the pollutant concentrations under a certain threshold is particularly difficult due to the strong nonlinearity and due to the high number of parameters (sometimes not manageable, as in the case of meteorological conditions) that can affect the concentrations at a certain time. In order to help Local Authorities in taking these decision, suitable Integrated assessment Models (IAMs) have to be formalized and implemented. In this work, the formalization and implementation of an IAM for the selecting of short-term actions is presented. The system is based on a forecasting phase and on a receding horizon approach for the selection of suitable emission control actions. The system has been applied with encouraging results to the management of PM10 levels over a domain including the metropolitan area of the city of Brescia in Lombardy.

Keywords: Modeling and identification of environmental systems, Environmental decision support systems, Air quality planning and control, Multi source environmental data integration, Natural and environmental systems

1. INTRODUCTION

In the past decades, the control of PM10 concentration has become one of the most relevant environmental problems (Landrigan et al., 2018). The selection of the set of actions to be taken in order to limit the population exposure to high levels of pollutants, local authorities but also citizens (see for instance (Manerba et al., 2018)) must take actions. In the last two decades a number of studies on the impact of different emission control strategy have been performed (Zhang et al., 2020), (Giannouli et al., 2011), (Li et al., 2020). In parallel, Integrated Assessment Models (IAMs) have been confirmed as suitable tools to help local authorities in selecting these actions, since they allow to take into account both air quality improvements and the social cost of the applied actions. In literature, a series of IAMs has been formalized, implemented and applied (Relvas et al., 2017) (Gimez Vilchez et al., 2019), usually allowing to treat the problem in the long-term period and considering the model in a steady-state condition when the optimization/control has to be designed (Turrini et al., 2018), (Pisoni et al., 2019), (Thunis et al., 2017).

The aim of this study is to develop a short-term Integrated Assessment Model to be used to (1) evaluate the impact of a single set of actions on air quality (scenario analysis) and to (2) select a set of optimal actions from a feasible set (Optimization). The main challenges of this work are related to the fact that, in in addition to the nonlinearity of the system to be controlled, in the short-term case the dynamic of the system cannot be neglected during the design of the controller. For the first time in literature, the problem of control of air quality is formulated and solved as a receding horizon control (Grune and Pannek, 2011).

In particular, the main goal of the decision support system will be to find the best short-term actions to be applied in order to reduce the daily mean concentration of particulate matter, trying to balance the improvements of air quality and the application costs.

This system has been applied to a known polluted zone which is the city of Brescia and its surroundings.

2. METHODOLOGY

The short-term air quality control problem has been formalized by means of a nonlinear receding horizon control (Carnevale et al., 2008) (Grune and Pannek, 2011) where the control law u^i in the time interval $[i, i+N-1]$ is expressed as a sequence of decisions:

$$u^i = \{u_{1,i}, ..., u_{M,i}, ..., u_{1,i+N-1}, .., u_{M,i+N-1}\} \quad (1)$$

where M is the number of the actions that Authority can apply and N is the prevision horizon.

Therefore, at each time step i the following optimal control problem is solved and the first step of the solution sequence u^i is applied:

$$\begin{aligned} &\min_{u^i} V_N(x_k, u^i, \cdot) = \min_{u^i} \sum_{k=i}^{i+N-1} V(x_k, u_{1,k}, ..., u_{M,k}, \cdot) \\ &\text{s. t.} \\ &x_{k+1} = f(x_k, u_k, \cdot) \qquad k = i, ..., i+N-1 \\ &u^i \in U \end{aligned} \tag{2}$$

where:

- V_N is the objective function to be minimized, i.e. the sum of the objective function V computed for each step;
- $f(x_k, u_k, \cdot)$ is the air quality model, allowing to estimate the evolution of the concentration of different pollutant in atmosphere as a function of concentrations computed at previous steps, of the input controlled variable (emissions) and of the uncontrolled ones (meteorology);
- x_k is the state of the system, i.e. the concentration of each species in each cell of the computational domain;
- u^i is the control sequence, as defined in 1;
- U is the feasible control set.

In the next sections, details about the model, the control sequence u^i and the feasible set U will be presented.

Air Quality Forecast The air quality model selected to forecast the pollutant concentration is the CAMx model (Environ, 2018). CAMx is an open source state-of-the-art multi-scale photochemical modelling for gas and particulate air pollution based on Fortran source code. CAMx simulates the emission, dispersion, chemical reaction and removal of pollutants by running the continuity differential equations forward in time for each chemical species on the basis of boundary conditions, initial conditions and weather predictions. More details on CAMx model and air quality integrated assessement modelling can be found in Carnevale et al. (2019) and Carnevale et al. (2018). In order to limit the effect of the input and model uncertainty on the overall system (Carnevale et al., 2016), a data assimilation technique based on optimal interpolation has been applied (Candiani et al., 2009) .

Control Sequence The control sequence u^i is strictly related to the concept of abatement measures, i.e. the short term actions (STA) that a Regional Authorities can apply in order to reduce the emissions in atmosphere of a certain number of pollutants. In this work, a short term action is considered as binary (i.e. the action is fully applied or not applied at all).

More in details, a single short term action can be defined in terms of:

- *Application map*: the area where the action is applied. Please note that, in order to consider u_k as a sequence of binary value, different application map means different actions.
- *Abatement factor*: the percentage of emission reduction obtained with the application of the action on a single cell of the application map. This variable won't be independent from the application area because different locations will have different drivers (activity that result in pollutant emission), i.e. traffic limitation in a city centre does not have the same effect of the same limitation on a rural area.
- *Cost*: each action has a cost; it can be expressed in terms of social disappointment or money.

2.1 Objective function

Usually, short-term air quality control concerns the need of a Regional Authority to maintain the daily concentration level of a pollutant below a certain threshold fixed by the European Directives, with a limited impact on the people living on a certain area. In order to consider both these aspects, the problem have to consider explicitly or implicitly both the number of occurrences of concentration over the threshold (exceedances) and the cost of the selected actions.

3. OPTIMIZATION PROBLEM SOLUTION

In this section, a sketch of the solution procedure has been presented. The resolution of the problem is compounded by two main facts:

- the CAMx model needs a strong computational effort to run;
- the f function modelled through CAMx is too complex to be considered and studied, due to the complexity and the enormous number of species and input variables to be considered to represent the phenomena involved in formation and accumulation of pollutants in atmosphere.

These two facts lead to the implementation of a simple, relatively fast, ad-hoc heuristic procedure, called only when the system forecast exceedances during the prevision horizon. Let w^0 be the solution at step 0 of the procedure, initialized considering all the possible action active on the whole prevision horizon N and, consequently, w^j the solution at the step j of the procedure. The solution u^i is computed by means of algorithm 1.

Algorithm 1 SELECTACTION(i, U, V, x_i, f, N)

$j \leftarrow 0$
for all $k \in \{i, \dots, i+N-1\}$ **do** // activate all actions
  for all $m \in \{1, \dots, M\}$ **do**
    $w^j_{mk} \leftarrow 1$
  end for
end for
while (stopping_rule) **do**
  $(m^*, k^*) \leftarrow \text{DROP}(w^j, U, V, x_i, f)$
  $j \leftarrow j + 1$
  $w^j_{m^*k^*} \leftarrow 0$
end while
$u^i \leftarrow w^j$
return u^i

where:

- w^j is the solution of the minimization problem at the step j of the procedure;
- $DROP(w^j, U, V, x_i, f)$ is a function selecting the indexes (m^*, k^*) of the single action to be deactivated at procedure step j (if any) on the basis of its cost and of its impact on air quality. In the selected implementation, the function tests the impact on air quality of each single action active at step j and compute its application cost. The action to be dropped is the one with higher cost and ensuring that its deactivation (1) causes a worsening in air quality under a certain threshold T and (2) does not cause an increasing in exceedances. If none of the actions ensures to respect of the conditions (1) and (2), the null set is returned.
- *stopping_rule* is an exit test, allowing the algorithm to end if the results of the *DROP* function is the null set.

4. CASE STUDY

The short-term IAM previously described has been tested for daily PM10 control in Brescia's province and its surrounding considering the concentration of Brescia's city as the feedback value. As particulate matter can have both *primary* and *secondary* origin, in order to reduce its concentration, the abatement measures aimed at reducing both primary particulate matter and/or nitrogen oxides (NO_x) emissions have to be considered.

For this work, the period chosen to run the simulations was the January 2011. This choice was related to the will to test the IAM in an adverse situation as winter months are normally characterized by higher values of particulate matter concentrations.

4.1 Domain

The methodology has been implemented and applied for the definition of short term plans for the city of Brescia. In particular, the domain is a 108 x 138 km^2 area (**Figure** 1) containing most of Brescia's province and the cities of Bergamo, Cremona and part of the external agglomerate of Milan. It has been further divided in 3726 squared cells, each with a $4km^2$ area as it can be observed in **Figure** 2.

4.2 Air Quality Forecast

As stated in Section 2, the air quality system used for the forecast is the CAMx model. In particular, the performances evaluation for the base case simulaton have been presented in Carnevale et al. (2018).

4.3 Control Actions

In this work, 4 groups of measures have been considered and tested:

- **Traffic Limitation/Car Ban** it proved to be a very effective measure. It may be applied temporarily (as for this case study) or permanently (the limited traffic zones in city centres). Traffic is one of the most polluting drivers that can be found, from the smoke generated by the internal combustion (it is a specially important NO_x drive) to the pollution caused by abrasions in the brakes and tires. The last factor is the deposed particulate matter that it manages to uplift from the pavement.

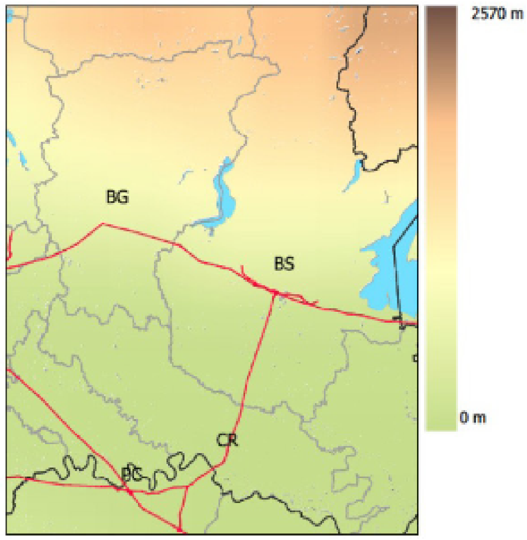

Fig. 1. Case study's domain.

- **Maximum Speed Reduction** in the main streets and highways, has usually very little influence at great scale but it shows good results on the air quality of the direct surrounding of the application area. This type of action was tested in Overschie (Rotterdam) Hodges et al. (2005) obtaining moderate reductions near the streets.
- **Wood Burning Limitation** it is an important action considering that in Brescia's province it counts for the 98% heating generated emissions.

As stated in section 2, for each action, 3 parameters have been specified, namely a zone where it is going to be applied, the abatement efficiency for every precursor and a cost. Figure 2 presents the considered application areas. For this case study, the choice was to divide the region of interest (Brescia's city and its surroundings) in 4 groups. The first group will contain only the cells inside the Municipality of Brescia (**Zone 1**). The second group will include instead, all the municipality in close proximity to Brescia (**Zone 2**), whilst the third and last group are the municipality in the second surrounding of Brescia. An extra zone had to be defined for one of the abatement measures which corresponds to the cells where the main streets and highways are within the area inside the domain (**Zone 4**). These zones are represented in **Figure** 2, Zone 4 was left aside and the rest of the province is shown in a different colour in order to ease the map's comprehension. The emission reduction due to the application of each action have been estimated starting from INEMAR database (ARPA Lombardia, 2011).

Table 1 presents the actions defined for the case study. Different activation areas can have different values of abatement efficiency, for example whilst in the city centre the main contributor to PM_{10} emissions is traffic (42% against the 30% of the particulate generated by wood burning) in the surrounding areas the main drive corresponds to the wood burning.

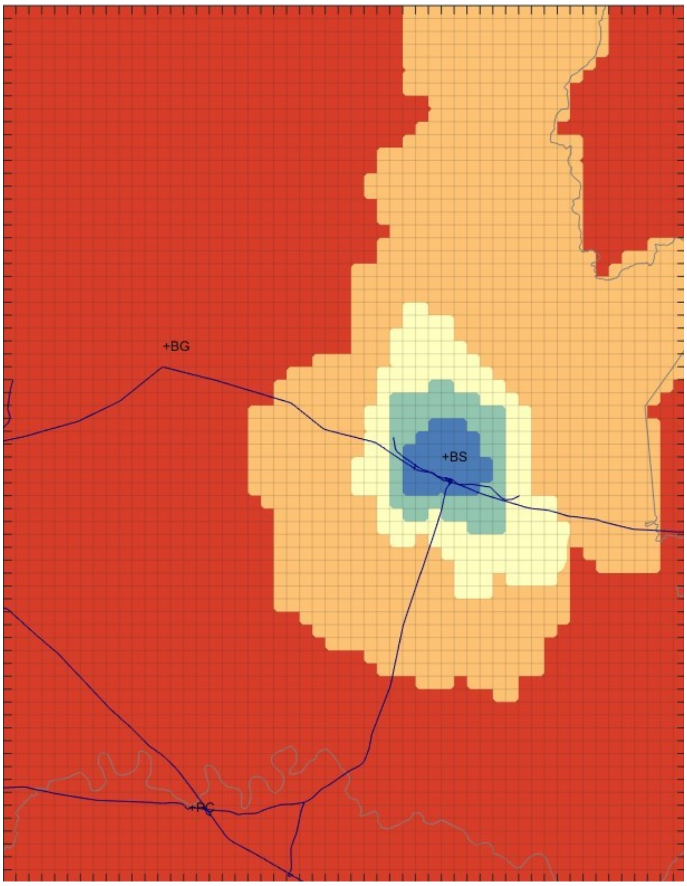

Fig. 2. Application maps of the actions considered in the case study.

Since it is very difficult to define a monetary cost for all the selected actions, the cost value for each level of actions was assumed to be proportional to the population affected by the measures.

Table 1. Abatement measures available.

	Action	**Area**	**% PM_{10} emission red.**	**% NO_x emission red.**	**Cost**
$u_{1,\cdot}$	Traffic Limitation	1	42%	51%	2
$u_{2,\cdot}$	Traffic Limitation	2	25%	52%	1
$u_{3,\cdot}$	Traffic Limitation	3	25%	52%	2
$u_{4,\cdot}$	Speed Reduction	4	23%	5%	2
$u_{5,\cdot}$	Wood Burning Limitation	1	30%	4%	1
$u_{6,\cdot}$	Wood Burning Limitation	2	50%	7%	2
$u_{7,\cdot}$	Wood Burning Limitation	3	50%	7%	2

Regarding the constraints related to the application of the considered measures, it could be stated that usually Authorities cannot apply the measures outside the principal cities without applying them to the city itself. For this reason, the set U of feasible u_k is defined by the constraints:

$$\begin{array}{ll} u_{1,k} \geq u_{2,k} & k = i, .., i+N-1 \\ u_{2,k} \geq u_{3,k} & k = i, .., i+N-1 \\ u_{5,k} \geq u_{6,k} & k = i, .., i+N-1 \\ u_{6,k} \geq u_{7,k} & k = i, .., i+N-1 \end{array} \quad (3)$$

4.4 Objective function

The objective function selected for the application is computed as the number of days where the PM10 daily mean concentration over the city of Brescia (Zone 1) is higher that $50\mu g/m^3$ (exceedances). In order to obtain the daily mean concentration over the city, the average of the concentration of each cell of Zone 1 is performed.

4.5 Results

The system has been tested on 3 different configurations, in order to evaluate its ability to prevent the exceedances in the urban area of Brescia. In this case, the air quality objective is set as the number of days when average daily mean PM10 concentration over all the cells of Zone1 is over the 50 $\mu g/m^3$ threshold.

- Test1: The application of the fully developed IAM (with the optimizer) was tested, based on a three day window horizon but the results u^i computed at time i are applied for all the prevision horizon. This test take into account the impossibility of the Local Authorities to announce to the population the actions every day.

- Test2: The application of the fully developed IAM (with the optimizer) was tested, based on a three day window horizon.

- TestMax: This test aims at studying the maximum possible effect of the available actions to reduce particulate matter concentration. In principle, this is a *scenario analysis* where all the measures are applied for each day.

These 3 tests have been compared with the *Base Case* scenario, computed by means of the *a posteriori* application of optimal interpolation to CAMx, i.e. computing the re-analysis field at time k using the measurement at the same time. Since these measurement are unknown for the prevision horizon, the results of the CAMx model for the forecast have been re-analysed extrapolating the last correction computed with available data.

Figure 3 and 4 presents the results of Test1 and Test2 compared to the Base Case. The impact of the control is limited in terms of exceedance days, even if the daily concentration reduction can reach quite high values ($> 10\mu g/m^3$). The main differences between the two cases lie in the behavior of the system in the interval from day 20 to day 23 In fact, due to higher dynamics of the Test2 controller, two exceedances can be avoided in the interval with respect to what happen in Test1.

In order to evaluate the impact of the two tested configuration, a comparison with the results obtained when all the actions are activated at each time is presented. As highlighted by **Figure** 5 the mean particulate matter

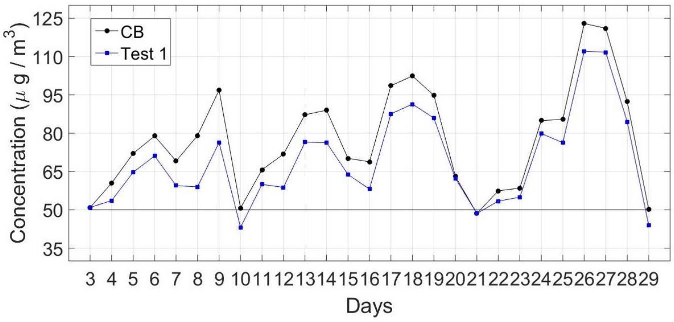

Fig. 3. PM_{10} concentration for uncontrolled (CB) and controlled ($Test1$) system.

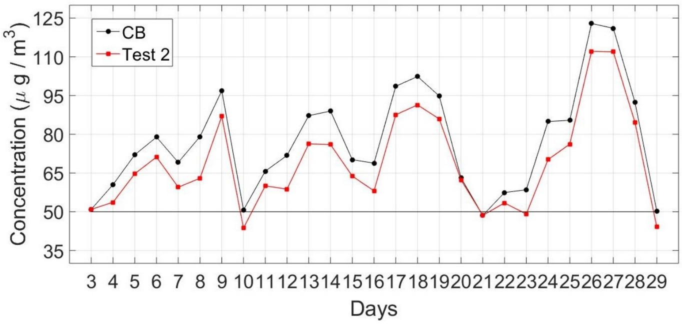

Fig. 4. PM_{10} concentration for uncontrolled (CB) and controlled ($Test2$) system.

concentration value over Brescia's cells has decreased of a minimum of almost 5 $\frac{\mu g}{m^3}$, and a maximum reduction of around 20 $\frac{\mu g}{m^3}$ (at day 9). Therefore, no strong reduction in exceedances is obtained.

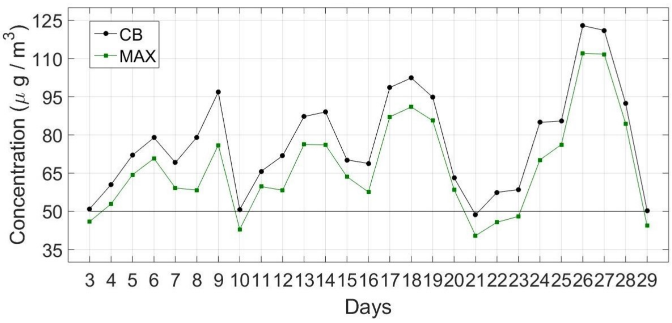

Fig. 5. PM_{10} concentration before (CB) and after the actions ($TestMax$).

Table 2 presents a comparison of the tests results in terms of exceedances, cost and mean PM10 concentration. It is clearly highlighted that the improvement in terms of exceedances is limited even if the reduction in terms of PM10 concentration is higher. Moreover, the control seems able to reach comparable results with respect to the Test Max (in particular if the mean concentration is considered) with a strong reduction in costs. The differences can be due to the fact that the forecasting system is not perfect, and for concentrations close to the threshold even a small error can lead to the application or not of the actions.

Finally, in order to better appreciate the impact of the control action all over the domain, the maps of the exceedances reduction with respect to the base case in the 3 tests are presented in Figure 6-8. The maps show how for all the tests, higher impact are not computed in the Brescia urban area but on the north of the city. This is due to the fact that outside the city there are strong emissions due to domestic heating by wood burning and the activation of the related action has higher effect there with respect to the city.

Test	**Exceedances**	**Cost**	$\mathbf{PM_{10}}$
Base Case	26	0	77.5
Test 1	24	268	69.0
Test 2	23	253	69.0
Test Max	21	351	67.3

Table 2. Results Comparison

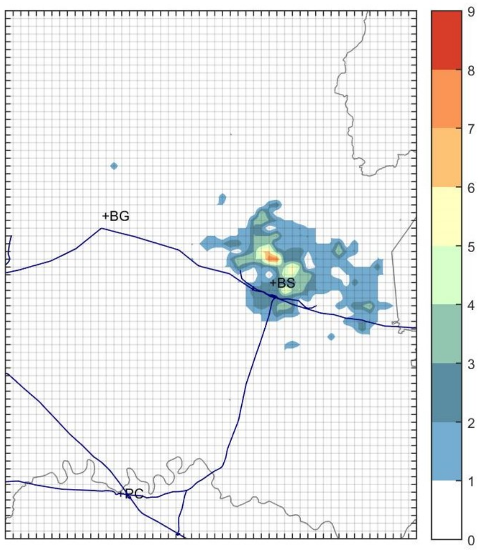

Fig. 6. Decreasing in exceedances with respect to Base Case for Test1.

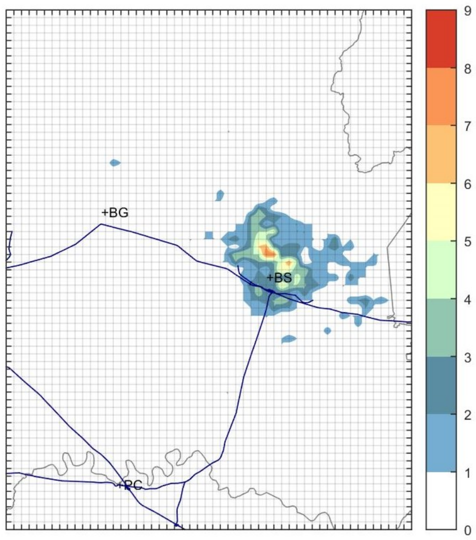

Fig. 7. Decreasing in exceedances with respect to Base Case for Test2.

5. CONCLUSION

The paper presents the implementation and application of a short term Integrated Assessment Modelling for air quality control. The problem is formulated as a receding

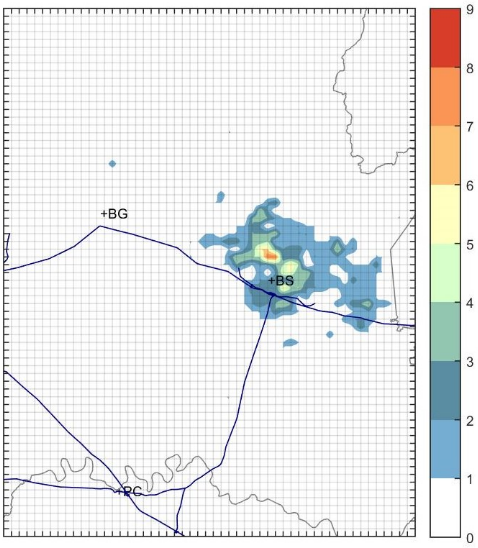

Fig. 8. Decreasing in exceedances with respect to Base Case for TestMax.

horizon control. The implemented system has been applied to control the exceedances of PM10 daily mean concentration over the area of the Brescia city in Lombardy. The results are encouraging even if the control performances are limited by the small sensitivity of the system to emission input. This is one of the key point to investigate in the near future, in order to evaluate if this behavior is linked to the forecasting model performances or to the algorithm implemented for the resolution of the optimization phase.

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