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RESEARCH ARTICLE

Optimal air quality policies and health: a multi-objective nonlinear approach

Helder Relvas[1] · **Ana Isabel Miranda**[1] · **Claudio Carnevale**[2] · **Giuseppe Maffeis**[3] · **Enrico Turrini**[2] · **Marialuisa Volta**[2]

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Abstract The use of modelling tools to support decision-makers to plan air quality policies is now quite widespread in Europe. In this paper, the Regional Integrated Assessment Tool (RIAT+), which was designed to support policy-maker decision on optimal emission reduction measures to improve air quality at minimum costs, is applied to the Porto Urban Area (Portugal). In addition to technological measures, some local measures were included in the optimization process. Case study results are presented for a multi-objective approach focused on both NO_2 and PM10 control measures, assuming equivalent importance in the optimization process. The optimal set of air quality measures is capable to reduce simultaneously the annual average concentrations values of PM10 and NO_2 in 1.7 and 1.0 μg/m^3, respectively. This paper illustrates how the tool could be used to prioritize policy objectives and help making informed decisions about reducing air pollution and improving public health.

Keywords Urban air quality planning · Integrated assessment modelling · Emission reduction scenarios · Surrogate model · Cost-benefit · Multi-objective approach

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✉ Helder Relvas
helder.relvas@ua.pt

1 CESAM, Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal

2 Department of Mechanical and Industrial Engineering, University of Brescia, 25123 Brescia, Italy

3 TerrAria s.r.l, Milan, Italy

Introduction

The changes in anthropogenic emissions in Europe and elsewhere, especially since the beginning of the 1990's, led to a decrease in the concentration values for several air pollutants. However, high concentration levels of particulate matter (PM), ozone (O_3), and nitrogen dioxide (NO_2) are still representing a serious risk to the environment and to the human health (WHO 2016). In Europe, in particular, exceedances with respect to the threshold values defined by the air quality directive (Directive 2008/50/EC) are still reported (EEA 2014, 2015). The effects of air pollution are mainly felt in urban areas, where more than half of the world population lives. The estimated numbers of premature deaths in EU-28 attributed to PM2.5, NO_2, and O_3 exposure are 403,000, 72,000, and 16,000, respectively (EEA 2015).

The air quality directive establishes the obligation of European Union (EU) member states to design and implement air quality plans (AQP) to improve air quality when limit values are not fulfilled. Moreover, member states should provide details on adopted measures or projects and estimates of the improvement of air quality planned, and the expected time required to attain the objectives. Several air quality plans were developed across Europe (Miranda et al. 2015) and in Portugal (CCDR-LVT 2006; CCDR–N 2007, 2010; Borrego et al. 2012).

The definition of effective strategies requires accurate and detailed information on the local situation, together with fast and simple tools to process it. One of the most commonly used approaches to deal with such problems at regional and local scales is based on the use of Eulerian chemical transport models (CTM) to evaluate the effects on air quality of a limited number of emission reduction measures (Miranda et al. 2015; Thunis et al. 2016b).

Integrated assessment models (IAM) can provide a more comprehensive support to policy-makers by identifying sets of cost-effective measures to improve the quality of the air. Typically, IAM describe the links between the emissions of pollutants, their atmospheric transport and chemical transformations, as well as the environmental and health impacts resulting from the application of policies (Carnevale et al. 2012b; Reis et al. 2005). They cover therefore the complete chain of events linking human activities (emissions) to health effects (impacts), and they are usually applied according with two main approaches: scenario analysis or optimization (Miranda et al. 2016; Thunis et al. 2016a). Within the first approach, emission reduction measures are selected on the basis of expert judgement or source apportionment and then they are tested (usually) through simulations by an air quality model. This approach does not guarantee that cost-effective measures are selected and only allows for 'ex-post evaluation' of impacts and costs. Optimization computes the most cost-effective measures for air quality improvement, by solving a minimization/maximization problem. In other words, the approach allows for the computation of the most efficient set of technical (i.e. end-of-pipe) and non-technical (i.e. behavioural) measures to be encouraged and/or introduced to reduce pollution, explicitly considering their impacts and costs.

The use of IAM as a policy-support tool in Europe has become more common in the recent decades. While RAINS/GAINS (Wagner et al. 2007) is the most widely used IAM for policy-making and negotiations at the European level, the need of operational IAM at the national level has originated country-specific adaptations like GAINS-Italy (D'elia et al. 2009), or the RAINS-NL (Aben et al. 2005). Other models such as USIAM (Mediavilla-Sahagún and Apsimon 2006), FRES-Finland (Karvosenoja 2008), LEAQ (Zachary et al. 2011), RIAT+ (Carnevale et al. 2012b), EVA (Brandt et al. 2013) or AERIS (Vedrenne et al. 2014, 2015) have been developed and applied to regional and local scales across Europe.

Nowadays, IAM, such as RIAT+, instead of applying computationally demanding CTM to provide emission/concentration relationships, exploit fast and simple surrogate models that can reproduce CTM results based on a small number of runs (Carnevale et al. 2012a). These surrogate models, however, are restricted to representing similar conditions, in terms of space and time characteristics, to those simulated by CTM.

Additionally, modern software packages implementing this approach can support decision-makers by offering a full set of views on the problem, starting from estimated emissions in each domain cell, to allocation of cost to different measures and sectors, to the external costs due to impacts on the population health and on ecosystems.

The RIAT+ tool has already been applied to several European regions, such as Alsace (France) (Carnevale et al. 2014) and Lombardy (Italy) (Carnevale et al. 2012b), providing useful information to policy-makers. Recently, it has been applied to Brussels (Belgium) and to Porto (Portugal) (Miranda et al. 2016). These studies are mainly focused on individual pollutants, which are assessed one by one. However, measures to cost efficiently improve the air quality can affect simultaneously the ambient concentration of more than one pollutant with different health benefits. Here, we aim to extend the application of RIAT+ to a multi-pollutant case and to a longer set of measures that include local measures proposed by policy-makers.

The main goal is to identify the most cost-effective mix of local policies for reducing human exposure to both PM10 and NO_2, being able to answer questions like 'in which sector(s) will our investments be more effective?', 'how much will we benefit in terms of health (avoided costs) from our investments?' or 'are the main control pollution options for both pollutants different?'.

This paper is organized as follows. 'The problem set-up for the Porto Urban Area in the northern region of Portugal' describes the case study, 'The computation of optimal policies' presents the RIAT+ setup, 'Results and discussion' shows its application focusing on the Pareto curve calculation and on the analysis of results. Finally, the 'Conclusions' section addresses the benefits of this kind of approach.

The problem set-up for the Porto Urban Area in the northern region of Portugal

Despite a progressive improvement of the air quality levels in the last years, the northern Portugal region and the Porto Urban Area in particular still present exceedances to the air quality limit values for PM10 and NO_2, both at urban traffic and background locations (Duque et al. 2016). Air quality plans (AQP) were already developed and submitted to the European Commission, namely: the AQP for the 2005–2008 period for PM10 at Braga Agglomeration, in the Northern Region (CCDR-N 2010), and the AQP for PM10 in 2004 in the Northern Region (CCDR-N 2007). The AQP were built using a bottom-up approach based on a close contact with several entities. These entities identified a list of measures and provided timelines and costs for their implementation. The impact of some of these measures was evaluated using an air quality model. Simulated PM10 and NO_2 levels improved with the considered measures, but some exceeding areas were still identified (Borrego et al. 2011, 2012). These AQP were developed without the help of IAM and it was not possible to identify the most cost-efficient measures to implement.

The Porto Urban Area, shown in Fig. 1, has been considered as an area in which air quality improvement measures should be concentrated. It represents the priority area for air quality (policy application domain—PAD). This important

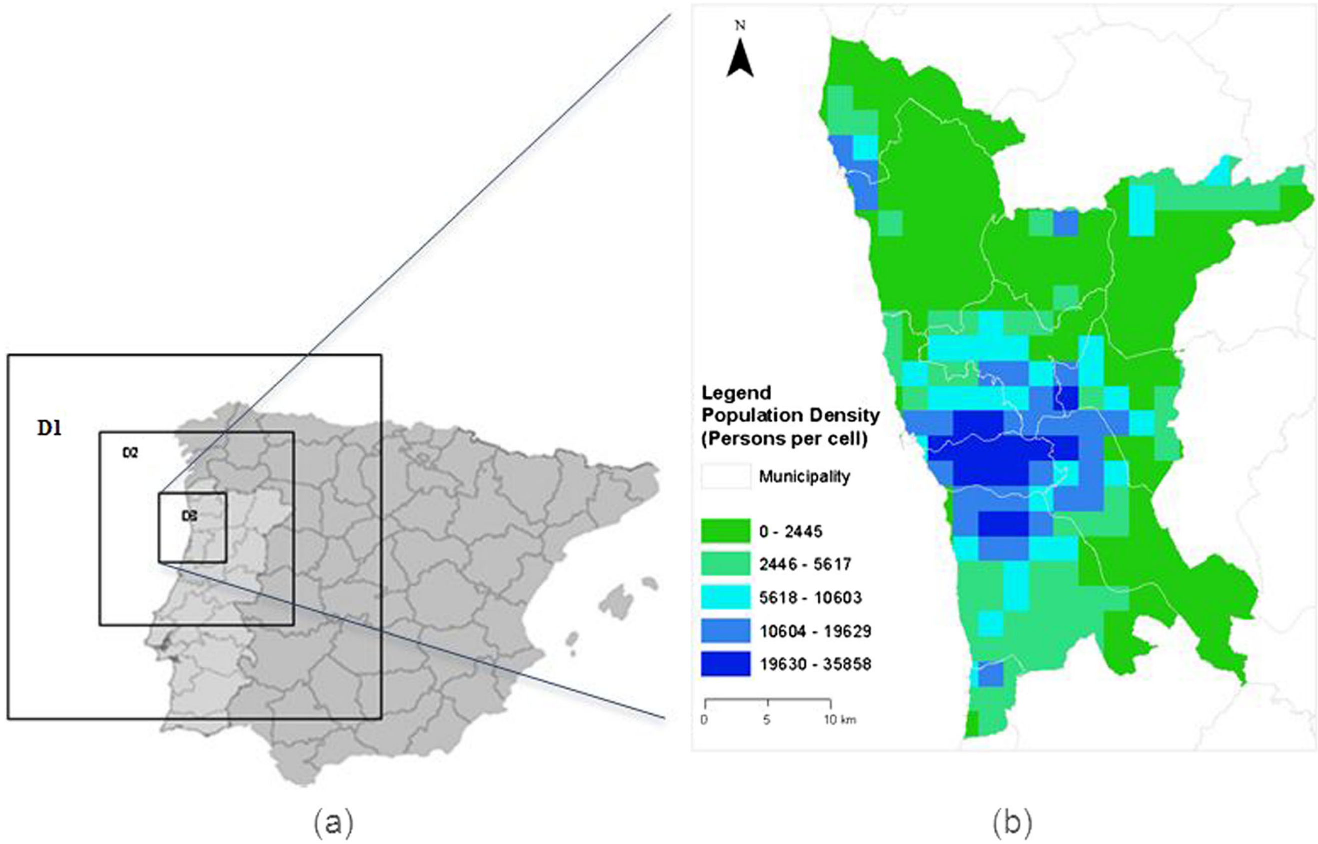


Fig. 1 The Porto Urban Area. **a** The simulation domains used in the TAPM modelling application. **b** population density in the Porto Urban Area

Portuguese sub-region is highly industrialized and the population ascend to 1,400,000 inhabitants (INE 2012).

In Table 1, the total annual emissions in the Porto Urban Area, corresponding to the most updated national emission inventory report (APA 2010), are listed.

Regarding the two pollutants focused on this paper, the main emission CORINAIR macrosectors (SNAP level 1) are 'production processes' and 'residential combustion' for PM10, 'road traffic' and 'industrial combustion' for NOx.

RIAT+ was applied to solve an optimization multi-objective problem in which an objective function is minimized. This function is composed by two air quality indexes (AQI), the yearly average NO_2 and the yearly average PM10 concentrations, and a cost index (CI) representing the cost due to the implementation of emission abatement measures. An additional key feature of such system is the substitution of the CTM by a suitable nonlinear surrogate model, identified through processing long-term CTM simulations, which allows a fast repetitive evaluation of the AQI. The RIAT+ requires a set of feasible emission reduction measures, which were selected using a detailed technology (end-of-pipe) dataset compiled by IIASA to Portugal (http://www.iiasa.ac.at; Amann et al. 2013), and a set of specific local measures that are a mixture of technical and non-technical measures involving a certain behavioural response from the policy subjects to achieve reduction (see 'The computation of optimal policies').

Three different RIAT+ settings are presented: a single pollutant optimization to improve exposure to NO_2 and PM10, separately, and then a multi-pollutant case (optimizing NO_2 and PM10 at the same time). The goal is to identify trade-offs between alternative emission reduction plans and to show how integrated assessment tools can support decision-makers in correctly setting priorities for improving air quality.

Definition of the surrogate model structure

The surrogate models selected in this work to reproduce the link between precursor emissions and secondary pollutant concentrations are artificial neural networks (ANN). ANN are surrogate models that can be applied to mimic the behaviour of nonlinear functions, such as the ones connecting precursor emissions with the secondary pollutant concentrations in atmosphere. The use of ANN to consider non-linearity is particularly relevant for the Porto Urban Area, because of its complex topography. In particular, a feed-forward neural network has been adopted and implemented.

ANN consist of several processing elements (nodes) organized in layers and linked to the nodes of the neighbouring

Table 1 Annual Porto Urban Area emissions (2009), for the different CORINAIR macrosectors (APA 2010)

ID	CORINAIR macrosector	NOX (t/year)	VOC (t/year)	NH_3 (t/year)	PM10 (t/year)	PM2.5 (t/year)	SO_2 (t/year)
1	Public power stations	2172	168	2	29	20	61
2	Residential combustion plants	1869	2701	0	2731	2667	487
3	Industrial combustion	3705	341	0	674	599	7392
4	Production processes	244	674	0	3100	763	123
5	Extraction and distribution of fossil fuels	0	4267	0	0	0	0
6	Solvent use	0	8119	0	41	41	0
7	Road transport	9807	3747	121	602	513	53
8	Other mobile sources and machinery	2581	211	0	344	344	592
9	Waste treatment and disposal	133	1334	303	326	0	635
10	Agriculture	33	68	1401	65	65	5
11	Nature	0	16,712	0	0	0	0

layers by connections called weights. Two different networks were created:

- the first ANN computes for each grid cell annual PM10 as a function of all precursor emissions (shown in the first row of Table 1) in the current and the adjacent cells;
- the second ANN computes for each cell annual NO_2 average as a function of all precursor emissions (shown in the first row of Table 1) in the current and the adjacent cells.

RIAT+ can also transform PM10 annual averages in daily number of exceedances, applying a linear relation, but this option was not considered. The focus was on annual averages only.

Design of experiments

The design of experiment's phase is devoted to the definition of the minimum set of CTM simulations required to provide data for the surrogate model calibration and validation. The main factors in terms of emission influencing pollution concentrations have been detailed in literature (Gabusi et al. 2008) and resulted in the selection of a series of 10 emission reduction scenarios inside the Porto Urban Area (Policy Application Domain—PAD). Given the high flexibility of the surrogate model structure adopted in this work (feed-forward neural network), this limited set of simulations allows identifying the ANN parameters with sufficient accuracy.

The 10 reduction scenarios were created, for each precursor emission, considering three emission levels, which were combined: the 2020 CLE (current legislation emissions) +15% (upper bound), the 2020 MFR (maximum feasible reduction) −15% (lower bound) and the average between these two extremes, to provide surrogate models with an intermediate point between CLE2020 and MFR2020. The 15% increase/decrease of emissions is needed in order to train the networks on a wider emission range, avoiding its application with inputs that are too close to the extremes, which could generate boundary effects. Table 2 presents the emission reduction simulated scenarios. The selected emission reduction combinations have been designed applying the factor separation analysis, as proposed by Gabusi et al. (2008).

For SO_2 emissions under scenario 1, an increase is expected in relation to the base case. This scenario is obtained considering the evolution of 2009 emissions under the CLE2020 scenario plus 15%. This SO_2 increase can be explained by an emission increase on macrosector 3 (due to industrial growth) and macrosector 8 (other mobile sources and machinery), between 2010 and 2020, with a weak decrease on the remaining macrosectors.

Emission maps for PM10 and NOx with respect to CLE2020 and MFR2020 can be found in Fig. 2. For additional emission maps (PM2.5, NH_3, SO_2, and VOC) please see Fig. S1 and Fig. S2-Online Resource.

Table 2 Emission reduction percentages (in comparison to the base case) for the 10 scenarios used for training and validation of ANN

Scenario ID	NOx	VOC	PM10	PM2.5	SO_2
1	-32.0%	−40.9%	−6.7%	−5.9%	15.6%
2	−45.7%	−49.5%	−26.3%	−21.0%	−20.2%
3	−57.9%	−57.6%	−43.5%	−35.0%	−49.7%
4	−57.9%	−49.5%	−26.3%	−21.0%	−20.2%
5	−45.7%	−57.6%	−26.3%	−21.0%	−20.2%
6	−45.7%	−49.5%	−43.5%	−35.0%	−20.2%
7	−45.7%	−49.5%	−26.3%	−21.0%	−49.7%
8	−57.9%	−57.6%	−26.3%	−21.0%	−20.2%
9	−57.9%	−49.5%	−43.5%	−35.0%	−49.7%
10	−57.9%	−49.5%	−26.3%	−21.0%	−49.7%

Finally, after training, the same surrogate model is applied hundreds of times on different sets of data (once for each training cell in the domain) which allows a robust estimation of ANN parameters.

Chemical transport model simulations

The air quality model simulations have been performed with 'The Air Pollution Model' (TAPM) (Hurley et al. 2005), developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). This model is a 3-D Eulerian model, composed of two modules that predict meteorology and air pollution concentrations based on fundamental fluid dynamics and scalar transport equations. The model was run in chemistry mode, with gas phase based on a semi-empirical mechanism entitled the generic reaction set (GRS), including 10 reactions for 13 species (Hurley 2008). Volatile organic compound (VOC) and PM components are speciated within TAPM based on particular profiles already available in the model in accordance to the different types of sources (Hurley 2008). TAPM model uses the following species for VOC: formaldehyde, higher aldehydes, ethane, alkenes, alkanes, toluene, xylene, and isoprene. PM10 and PM2.5 emissions are inputted to the model for the different types of sources. NOx and NO_2 emissions are directly inputted to TAPM and a fraction of NOx is provided, per type of source, to estimate NO.

The meteorological module of TAPM has been set up on three nested domains with a horizontal resolution of 12.5, 5, and 2 km side-length, respectively domains D1, D2, and D3, all centred on the Porto Urban Area (see Fig. 1). The chemical transport module is focused on the smaller domain using inflow boundary conditions from the outer domain. Background concentrations were also used by the model to initialize pollutant concentrations. These background and boundary concentrations were obtained estimating the annual average of the background air quality values measured by the monitoring sites in the study regions.

The horizontal resolution used for the smaller domain is constrained by the high computational demand associated to the number of simulations that have to be done to train the RIAT+ system. This spatial resolution does not allow estimating urban local hot spots.

The model was applied for one entire reference year (2012) with 25 vertical grid layers. The emission data for year 2009 (provided by Portuguese Environment Agency) by pollutant and activity sector was spatially and temporally disaggregated (using hourly emission profiles per macrosector) to obtain the resolution required for the selected simulation domain.

Modelled concentrations by TAPM were compared against measurements from the Portuguese Agency for the Environment monitoring network (http://www.apambiente.pt/). Monitoring stations inside the domain were considered for the model validation, which was based on the FAIRMODE methodology. Details on this validation, namely performance skills, can be found in (APPRAISAL 2015). Moreover, TAPM was the used model in the scope of Northern Region AQP (Borrego et al. 2011, 2012) and was also applied to assess the impact of improvement measures in a scenario mode (Duque et al. 2016).

Keeping the same meteorology and model configuration, 10 additional air pollution simulations have been performed on the Porto Urban Area domain, corresponding to the list in Fig. 2.

The selected ANN structure considers input coming from four contiguous quadrants, thus considering prevalent wind directions. Different literature shapes/configurations can be used (Carnevale et al. 2012a, Clappier et al. 2015). This configuration has the advantage of being adjustable to different conditions by modifying the dimensions of the quadrants. With this structure, ANN has four input values per precursor (one for each quadrant) see Fig. S3-Online Resource).

The ANN inputs (i.e. the sum of precursor emissions over the quadrants) are pre-processed by means of a normalization procedure ([0, 1]), using MATLAB code in order to ensure convergence of backpropagation estimation methods. To obtain the data needed to train these models, a design of experiment phase is required, in order to define the minimum set of CTM simulations, with the maximum information content. The emission scenarios selected in these phase and their relative PM10 and NO_2 concentrations, simulated by means of CTM, are then used for the surrogate model training and validation.

The identified ANN are characterized by the features shown in Fig. S5-Online Resource. The scatter plots in Fig. 3 show the comparison between the output of the neural network models for PM10 and NO_2 annual mean concentration and the CTM results. The scatter plots highlight that all points are very close to the bisecting line, even if the identified neural networks slightly underestimate the PM10 index.

The normalized root-mean-square error (RMSE) is 0.35 and 0.37 for PM10 and NO_2, respectively. The correlation coefficient is 0.95 for PM10 and 0.97 for NO_2 this confirms that ANN has the capability to simulate the nonlinear source–receptor relationship between concentrations and the emission of its precursors.

The computation of optimal policies

In this case study, we choose the year 2020 for optimization, meaning that the optimal results will suggest which measures should be applied on top of the CLE 2020, assuming that boundary emissions have been modified accordingly. In relation to the technology, it is possible to replace old technologies with new ones, in macrosector 2 and macrosector 7. This

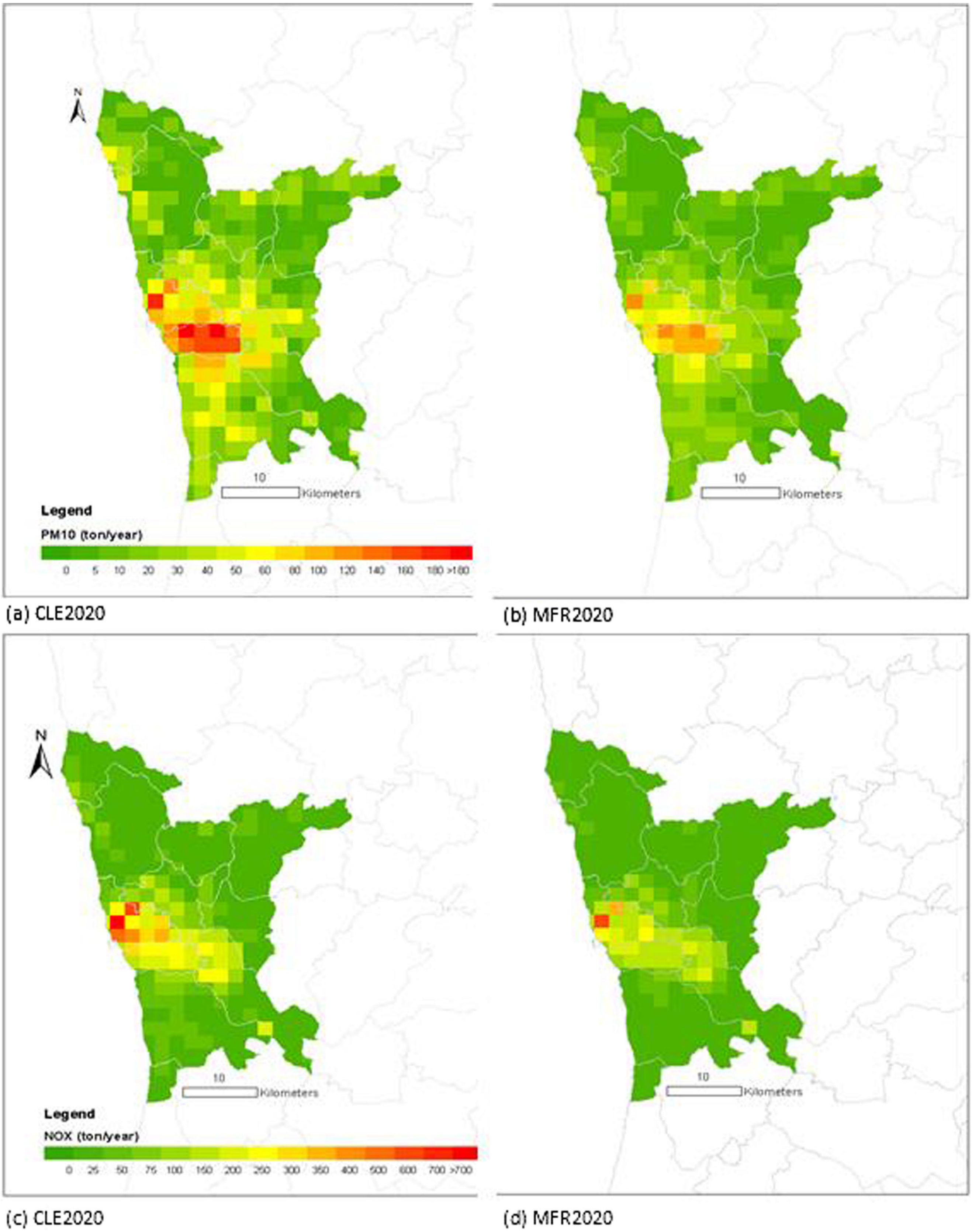


Fig. 2 Total primary gridded emissions at 2 × 2 km^2 resolution for the CLE2020 (**a**, **c**) and the MFR2020 (**b**, **d**) inside the Porto Urban Area for PM10 and NOx (units: Mg year^{-1})

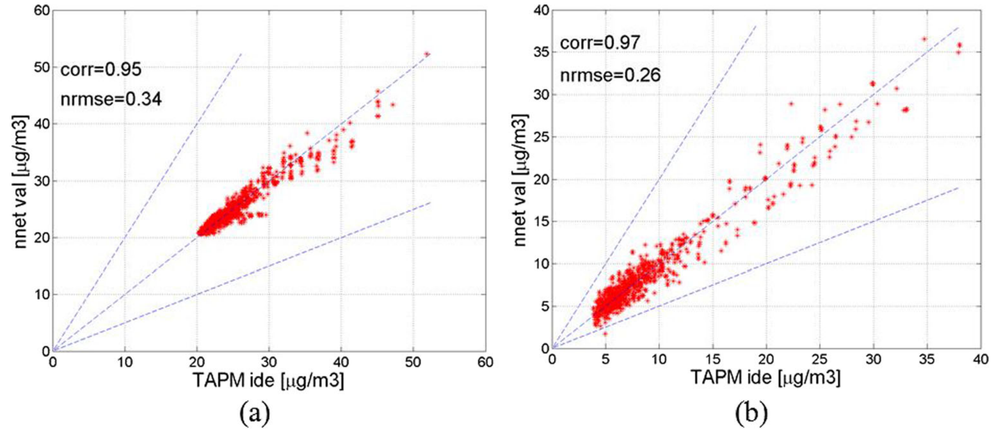


Fig. 3 Scatter plots between TAPM (*x*-axis) and neural network (*y*-axis) for **a** yearly PM10 [µg/m^3] and **b** NO_2[µg/m^3] index

option allows for the replacement of old heating systems with new ones and old EURO emissions standard with more advanced ones. For other macrosectors, technologies foreseen by legislation in force are supposed to remain in place. This analysis also used some local measures that were discussed informally with local policy-makers. After chosen these options, three different configurations have been considered, minimizing respectively:

I. annual mean concentrations of NO_2;

II. annual mean concentrations of PM10;

III. a joint index composed by NO_2 and PM10 assuming equivalent importance (weight) in the optimization process. The user may give a different weight to the different pollutants in the optimization process.

In terms of emission reduction measures and related costs, both the end-of-pipe technology datasets developed by IIASA for the GAINS EUROPE model, and some local measures have been used.

The default RIAT+ database with abatement technologies available for different macrosectors (e.g. non-industrial combustion and transport) is the same as the one that was derived from GAINS Europe in the frame of the OPERA LIFE+ project (Carnevale et al. 2012a). This database includes data related to the different emission activities (unabated emission factor, activity level…) and technology details (removal efficiency, potential application rate, unit cost…). The GAINS dataset for Portugal includes the measures available on TSAP Report #10 (Amann et al. 2013), which were carefully selected and adapted to be used in the Porto Urban Area, amounting to 130 specifically selected measures for the Porto Urban Area. A table with all the measures under consideration, an indication of the macrosectors that they affect, and the removal efficiencies for the different pollutants is included in (APPRAISAL 2015).

In terms of local measures, they are a mixture of technical and non-technical and they involve a certain behavioural response to achieve reductions. Three measures have been considered:

I. Free park and authorized use of bus lanes for electric vehicle owners in Porto Urban Area. In addition, they can top up their batteries from one of the 27 public (441 total national) chargers for free. It is assumed that about 1000 drivers are susceptible to use the available parks inside the region, implying a 5€ loss (average parking price) per parking place per day. Assuming that there are 251 working days in the year, the total cost of the measure, resulting from the loss of tax revenue is 1.20 M€/year. The emission reduction provided by COPERT4 model, assuming the replacement of 750 old diesel and gasoline light vehicles by new 100% electric ones, is presented on Table 3.

II. Electric Taxi Programme implies the replacement of 500 diesel taxis from a total of 3217 (see Fig. S4-Online Resource) by new 100% electric ones. It is part of the National Reform Programme with a total cost estimated on 1.6 M€ (fiscal incentives). To estimate the resultant emission reduction, the COPERT4 emission model was used considering 1.4–2.0 cylinder diesel vehicles and EURO 4 standards. An average of 65,000 km driven by vehicle by year was assumed. The resultant emission reduction is shown on Table 3.

III. The Bike Programme is part of the National Reform Programme, which aims to make available 6000 new bicycles on free-shared systems by 2020 in Portugal. The programme gives students, municipal staff, and general public more one reason to ride a bike to work, or to do small trips. Considering that 25% of the new bicycles will be allocated to Porto Urban Area, the estimated costs of the systems can ascend to 0.20 M€/year. The expected emission reduction (considering a daily reduction of 1000 passenger cars in circulation, and an average of 12,000 km driven by vehicle by year) is shown on Table 3.

Table 3 Emission reductions in relation to CLE, corresponding to the optimal policies computed for point D of the Pareto curve (joint NO_2 and *PM10* optimization)

CORINAIR macrosector	Optimal policies computed	Main pollutant reductions (t)			Application rate (%)	
		NOx	VOC	PM10	CLE	Optimal
1	Combustion modification on existing oil and gas power plants	133.6	0	0	80	100
2	Fireplace improved	0	1484.1	868.2	15	92.3
2	Fireplace new	0	58.4	48	5	7.7
3	Combustion modification on solid fuels fired industrial boilers and furnaces	74.3	0	0	20	100
3	Combustion modification on oil and gas industrial boilers and furnaces	57.8	0	0	50	100
6	Incineration	0	201.4	0	80	100
6	Closed (sealed) degreaser: use of chlorinated solvents	0	48.7	0	29	42.4
7	EURO 6 on light duty diesel road vehicles	140.5	426.6	64.7	44.4	46.4
7	Electric Taxi Programme	33.6	76.6	9.8	0	100
7	Bike Programme	3.7	8.5	1.1	0	100
7	Free Park for Electric Vehicles	3.6	8.4	1.1	0	100
8	Combustion modification on medium vessels using marine diesel fuel	615	0	0	23.4	100

Results and discussion

Figures 4 and 5 show NO_2 and PM10 annual concentration values spatially averaged for the entire simulation domain for the different optimal solutions. We can see from Figs. 4 and 5 the policy outcomes computed with the air quality indices described above. Annual averaged NO_2 concentrations obtained with an optimization focused on NO_2 only (Fig. 4, green curve) obviously provides the maximum NO_2 index reduction, whereas an optimization focusing on PM10 only would lead to the worst NO_2 index value (blue curve).

Co-benefits are estimated with this RIAT+ application. With similar costs is possible to obtain NO_2 and PM10 concentration reductions instead of getting the reduction of only one compound. This is possible because measures were selected to simultaneously improve both pollutants without higher costs. This mathematical optimum results provided by RIAT+ are calculated under the specific set of emissions, abatement measures, and abatement costs.

Figure 6 details solution D in terms of emission reductions and implementation costs beyond CLE, aggregated per CORINAIR macrosector. The left side panels show emission reductions beyond CLE, and the right side ones the cost beyond CLE, entailed by the optimal policy related to the point D of the previously illustrated Pareto curve. For the yearly NO_2 optimization (Fig. 6c, d), emission reductions should be applied to macrosectors 2, 1, 3, 7, and 8 (residential/commercial combustion, public power stations, industrial combustion, road transport, and other mobile sources, respectively) even if the costs are mainly related to macrosector 2 (residential/commercial combustion). This is explained by the fact that, although no direct NO_2 emission reduction be expected from macosector 2, some chemical reactions involving VOC, NO_X, and O_3 may be responsible by this outcome.

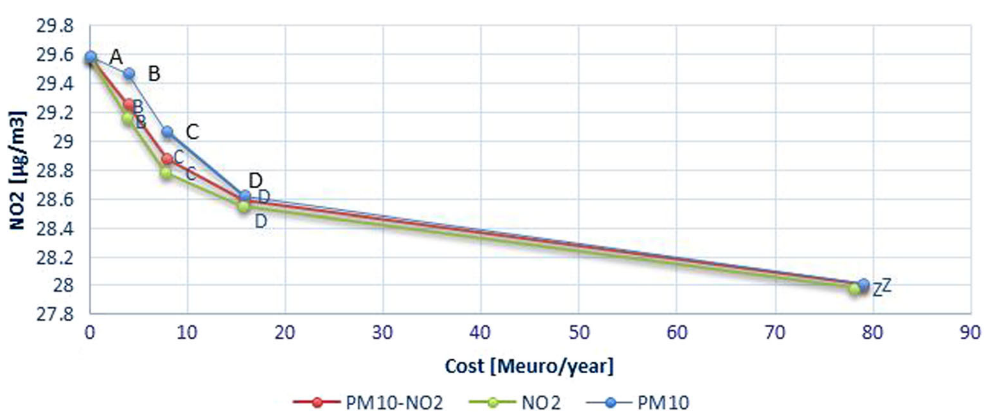


Fig. 4 Pareto optimal policies computed considering the three selected optimizations, with cost of policy implementation (*x*-axis) and NO_2 yearly average (*y*-axis). The *green line* corresponds to the NO_2 optimization, the *blue line* to the PM10 optimization, and the *red line* to the multi-pollutant case

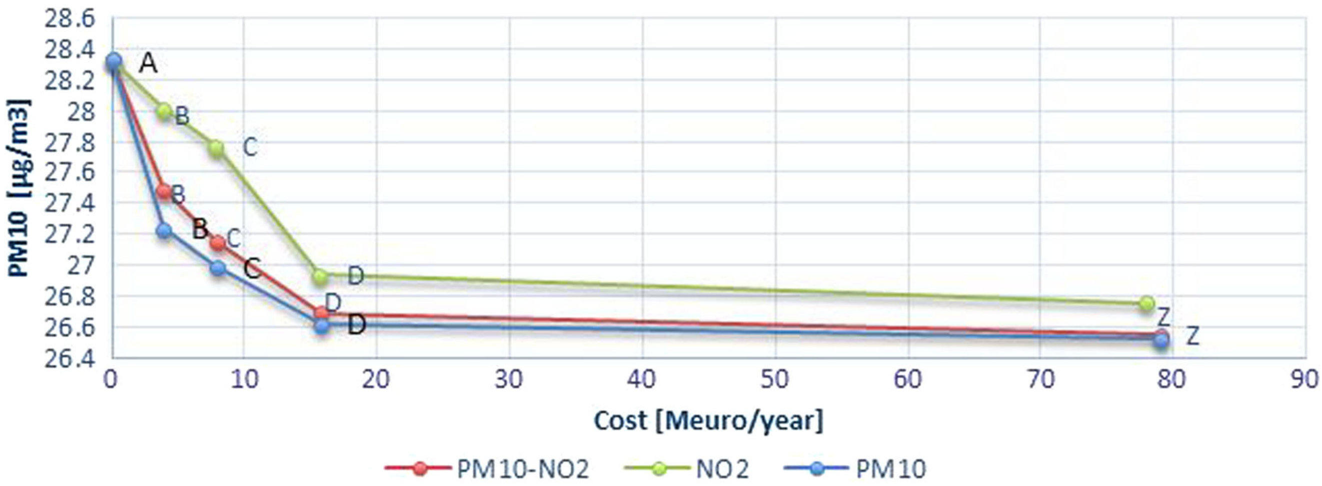


Fig. 5 Pareto optimal policies computed considering the three selected optimizations, with cost of policy implementation (*x*-axis) and PM10 yearly average (*y*-axis). The *green line* corresponds to the NO_2 optimization, the *blue line* to the PM10 optimization, and the *red line* to the multi-pollutant case

On the other hand, actions (i.e. emission reductions) are more efficient in macrosectors 2, 7, and 8 for PM10 (Fig. 6e, f) with higher costs in macrosector 2. For the multi-pollutant optimization, the emission reduction policy is similar to the NO_2 one but with an investment increase on macrosector 2 and a decrease on macrosector 8 (Fig. 6a, b). The main difference between the PM10 and the multi-pollutant optimization case is related with the investment effort on macrosector 2, mostly strong in case of single PM10 optimization.

Point D solution, in the case of joint NO_2 and PM10 optimization, allows to obtain an annual averaged NO_2 concentration reduction of 1.0 μg/m^3 and a PM10 concentration reduction of 1.7 μg/m^3 over Porto Urban Area domain. Higher concentration reductions are expected over the Porto municipality where the population density is higher. The expected concentration levels of NO_2 and PM10 are presented on Fig. 7.

As we can see from Table 3 the main NO_2 reductions are achieved by action on 'combustion modification on medium vessels' and replacing old 'light duty diesel road vehicles' by EURO 6 class ones. In relation to PM10 evidently 'fireplace improved' and 'new fireplace' can strongly reduce the emissions. The three local measures have a limited potential to reduce both NO_2 and PM10 emissions; however, municipal authorities will possibly more easily implement them.

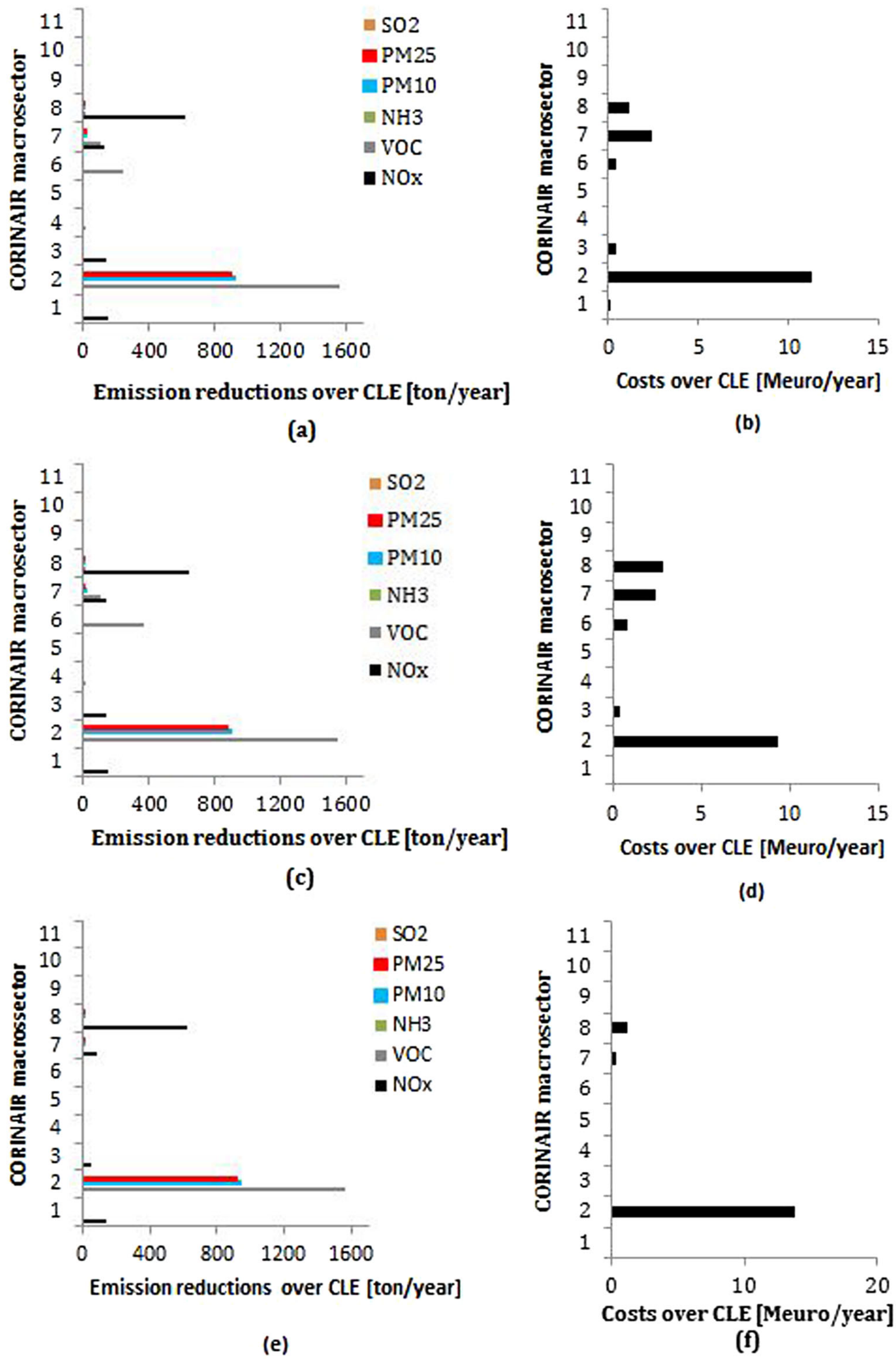
Figure 7 presents the spatial distribution of NO_2 and PM10 annual concentration values, for the point D of the Pareto curve. Based on this optimized emission reduction scenario represented by point D, it is expected a concentration of NO_2 lower than 40 μg/m^3 (the air quality limit value). In the case of PM10, the air quality limit value of 40 μg/m^3 will continue to be exceeded, mainly in Porto municipality.

As we can see from Table 3, the main NO_2 reductions are achieved by acting on 'combustion modification on medium vessels', and replacing old 'light duty diesel road vehicles' by EURO 6 class ones. The CLE application rate of EURO 1 class (0.2%) should be reduced to zero, the EURO 2 class should be reduced from 1.4 to 1.1, the EURO 3 should be reduced from 4.6 to zero, and the EURO 5 from 37.4 to 31.8. In relation to PM10 'fireplace improved' and 'new fireplace' can strongly reduce the emissions. The 'fireplace improved' application rate should increase from 15 to 92.3% and the new 'new fireplace' should increase from 5 to 7.7%. The three local measures have a limited potential to reduce both NO_2 and PM10 emissions; however, municipal authorities will possibly more easily implement them.

RIAT+ can also produce maps for indexes computed ex-post, such as years of life lost (YOLL), using calculated quality indexes. The YOLL indicator provides estimates of potential life years lost due to premature mortality. RIAT+ methodology is based on the ExternE approach (Bickel and Friedrich 2005). The impact on the entire population is obtained by summing life expectancy over all affected cohorts, weighted by the age distribution. Only ages above 30 have been included in the calculations because the underlying cohort studies did not include younger people.

In the particular case of PM, ExternE uses Pope epidemiologic study extending it to PM10. The conversion of exposure–response functions between PM10 and PM2.5 is quite common for mortality effects, but it is not scientifically supported yet. Usually the ratio 0.6–0.8 between PM2.5 and PM10 is used as the factor (Sjöberg et al. 2009). If the effect is mainly related to PM2.5, this conversion factor may be relevant. If coarse particles are as important as fine, this down-scaling of effects is not really needed. ExternE assumes that the impact on mortality of anthropogenic

Fig. 6 Emission reductions (*left*) and costs beyond CLE (*right*), corresponding to solution D, for **a**, **b** joint NO_2 and PM10 optimization; **c**, **d** yearly NO_2 optimization; **e**, **f** PM10 optimization



PM10 and PM2.5 would almost be of similar size, while for respiratory morbidity, the contribution of the coarse fraction may be greater.

Figure 8 shows the spatial distribution of the difference between YOLL estimated for the base case and considering the implementation of the measures shown on Table 3 (Solution D).

The spatial distribution of the YOLL values indicates higher health effects in terms of years of life lost in the central-western part of the domain, where both concentrations and population density are highest (see Figs. 1 and 2). The simulated concentration values at 2 km cell level, however, mask the presence of high-concentration hotspots at the local

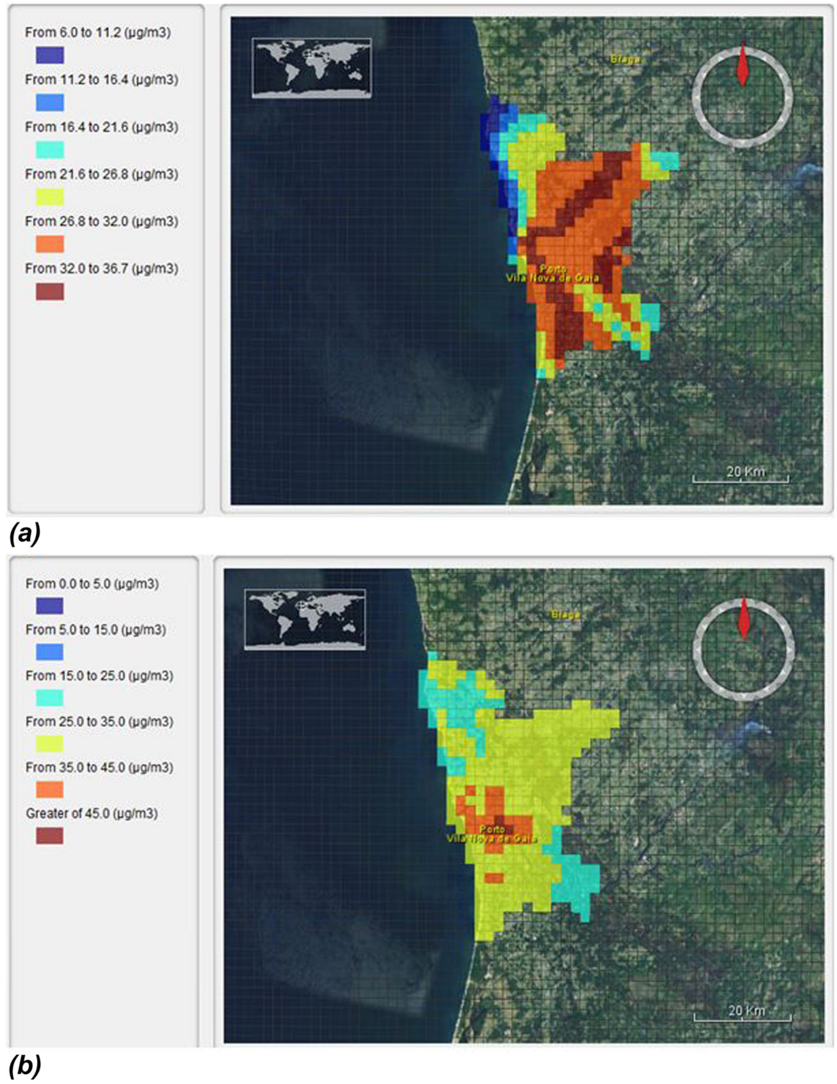


Fig. 7 RIAT+ NO_2 concentration ($\mu g\ m^{-3}$) (**a**) and PM10 concentration ($\mu g\ m^{-3}$) (**b**) for the point D of the Pareto curve

scale and could underestimate YOLL. Moreover, the exposure assessment is based on a simple population distribution map, by age classes, and an exposure model taking into consideration activity population patterns would improve results.

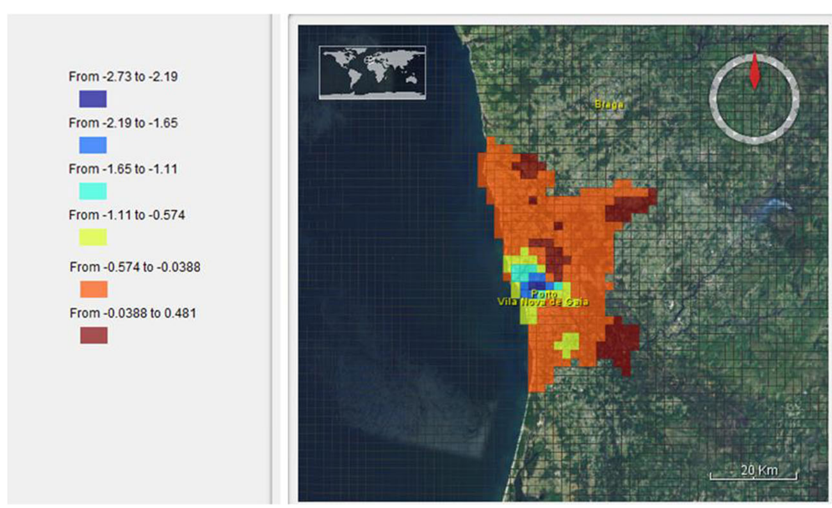


Fig. 8 Difference between years of life lost (YOLL) [months/person] estimated for the base case and considering point D of joint NO_2 and PM10 optimization

Conclusions

Optimization approaches can be used to contribute to a more effective solution of the problem of pollutant concentration reduction in atmosphere; however, fast surrogate models that link precursor emissions to pollutant concentrations are needed. In this work, ANN has proven to be a viable substitute for highly time-demanding deterministic models.

RIAT+ tool allows evaluating the joint reduction of different pollutants while considering a large sets of measures. In this particular case, measures to simultaneously reduce NO_2 and PM10 were selected in order to obtain the most cost-effective solution. It was possible to realize that concentration reductions of both pollutants can be obtained with similar costs to those focused only on one pollutant. However, optimized results depend on the provided specific set of emissions, abatement measures, and abatement costs. Thus, the more reliable, realistic, and representative the underlying information is, the higher is the tendency of this optimum to match a real policy outcome. Different input data and assumptions will inevitably result in different optima.

The presented application of RIAT+ to the Porto Urban Area has led to the following conclusions. Firstly, reductions of both PM10 and NO_2 concentrations will be achieved mainly through actions on traffic and domestic sectors. Secondly, when we are looking to a sub-regional domain, there is an opportunity for local actions. Some of these local measures are more easily applied because they are not dependent of specific legislation or national budget. However, the effect of including the selected local measures is too low in comparison to the impact of the technological ones, and in this particular case, study technological measures are needed to obtain a significant air quality improvement.

RIAT+ can give in approximately 5 min package of measures that under a specific level of ambition produces the highest reduction in concentrations at a reasonable cost, as opposed to other packages of measures. However, in some cases, the tool may be superseded by the legal obligation to comply with the law (e.g. Directive 2008/50/EC), as well as other political considerations and public acceptance.

One of the biggest difficulties of the previous Northern Region AQP was to identify the most efficient measures that could be applied with important improvements. This RIAT+ study helps to identify and to select the most cost-effective measures. It did not consider the long list of individual measures proposed by the several entities in the scope of the 2011 AQP but confirmed the most important sectors mentioned in this AQP. Moreover, the capability to consider the benefits of these measures and their implementation costs together is a very important benefit, which answers some of the policy-makers' demands. Finally, being able to simultaneously consider PM10 and NO_2 (the most critical pollutants in the Porto Urban Area) measures and effects is also advance. RIAT+ is, therefore, a tool whose capabilities allow informing the elaboration, review, and negotiation of air quality plans in general, and with capacities to deal with a multi-pollutant case.

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References

Aben, J., Hettelingh, J.-P. & Schöpp, W (2005) RAINS-NL: an integrated assessment model to support Dutch air quality policy making. Informatics for environmental protection - networking environmental information

Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Hetelingh J-P, Heyes C, Holland M, Kiesewetter G, Klimont Z, Rafaj P (2013) Policy scenarios for the revision of the thematic strategy on air pollution TSAP report #10. Version 1.2. International Institute for Applied Systems Analysis IIASA, Vienna

APA, P. E. A (2010) Portuguese Informative Inventory Report 1990–2009. Submitted under the UNECE convention on longrange transboundary air pollution Agência Portuguesa do Ambiente, Amadora, Portugal (2010)

APPRAISAL, P. O. A. P. P. F. A. O. I. S. A. R. A. L. S (2015) Guidance on integrated air quality and health assessment systems, deliverable 4.3 guidance document evaluation Tier2

Bickel P, Friedrich R (2005) ExternE: externalities of energy, methodology 2005 update . IER, University of Stuttgart, Stuttgart**Tech. Rep.**

Borrego C, Monteiro A, Carvalho A, Miranda A, Coelho D, Sá E, Lopes M, Sousa S (2011) Air quality plans for the northern region of Portugal: improving particulate matter and coping with legislation. INTECH Open Access Publisher, Croatia

Borrego C, Sá E, Carvalho A, Sousa S, Miranda A (2012) Plans and programmes to improve air quality over Portugal: a numerical modelling approach. Int J Environ Pollut 48:60–68

Brandt J, Silver JD, Christensen JH, Andersen MS, Bønløkke JH, Sigsgaard T, Geels C, Gross A, Hansen AB, Hansen KM (2013) Contribution from the ten major emission sectors in Europe and Denmark to the health-cost externalities of air pollution using the EVA model system—an integrated modelling approach. Atmos Chem Phys 13:7725–7746

Carnevale C, Finzi G, Guariso G, Pisoni E, Volta M (2012a) Surrogate models to compute optimal air quality planning policies at a regional scale. Environ Model Softw 34:44–50

Carnevale C, Finzi G, Pisoni E, Volta M, Guariso G, Gianfreda R, Maffeis G, Thunis P, White L, Triacchini G (2012b) An integrated assessment tool to define effective air quality policies at regional scale. Environ Model Softw 38:306–315

Carnevale C, Finzi G, Pederzoli A, Turrini E, Volta M, Guariso G, Gianfreda R, MAFFEIS G, Pisoni E, Thunis P, Markl-Hummel L, Blond N, Clappier A, Dujardin V, Weber C, Perron G (2014) Exploring trade-offs between air pollutants through an integrated assessment model. Sci Total Environ 481:7–16

CCDR-LVT, L. R. C. A. D. C (2006) Plans and programmes to improve air quality in the Region of Lisbon and Tagus Valley. Lisbon

CCDR–N, N. R. C. A. D. C., UA (UNIVERSITY OF AVEIRO) (2007) Plan to improve air quality in the Northern Region: PM10–2004, O3–2004/2005, Technical Report No. AMB–QA–07/2007. Porto

CCDR–N, N. R. C. A. D. C., UA (UNIVERSITY OF AVEIRO) (2010) Plan to improve air quality in the Braga Agglomeration 2005–2008, Technical Report No. AMB–QA–03/2010. Porto

Clappier A, Pisoni E, Thunis P (2015) A new approach to design source–receptor relationships for air quality modelling. Environ Model Softw 74:66–74

D'elia I, Bencardino M, Ciancarella L, Contaldi M, Vialetto G (2009) Technical and non-technical measures for air pollution emission reduction: the integrated assessment of the regional air quality management plans through the Italian national model. Atmos Environ 43:6182–6189

Duque L, Relvas H, Silveira C, Ferreira J, Monteiro A, Gama C, Rafael S, Freitas S, Borrego C, Miranda AI (2016) Evaluating strategies to reduce urban air pollution. Atmos Environ 127:196–204

EEA (2014) Air quality in Europe—2014 report, EEA report no 5/2014. European Environment Agency, Denmark

EEA (2015) Air quality in Europe—2015 report, EEA report no 5/2015. European Environment Agency, Denmark

Gabusi V, Pisoni E, Volta M (2008) Factor separation in air quality simulations. Ecol Model 218:383–392

Hurley, P (2008) TAPM V4. Part 1: technical description. CSIRO Marine and Atmospheric Research Paper No. 25. CSIRO Marine and Atmospheric Research Group

Hurley PJ, Physick WL, Luhar AK (2005) TAPM: a practical approach to prognostic meteorological and air pollution modelling. Environ Model Softw 20:737–752

INE I (2012) Censos 2011 resultados definitivos-Portugal. Instituto Nacional de Estatística, IP, Lisboa

Karvosenoja N (2008) Emission scenario model for regional air pollution. Finnish Environment Institute, Helsinki

Mediavilla-Sahagún A, Apsimon HM (2006) Urban scale integrated assessment for London: which emission reduction strategies are more effective in attaining prescribed PM10 air quality standards by 2005? Environ Model Softw 21:501–513

Miranda A, Silveira C, Ferreira J, Monteiro A, Lopes D, Relvas H, Borrego C, Roebeling P (2015) Current air quality plans in Europe designed to support air quality management policies. Atmospheric Pollution Research 6:434–443

Miranda AI, Relvas H, Viaene P, Janssen S, Brasseur O, Carnevale C, Declerck P, Maffeis G, Turrini E, Volta M (2016) Applying integrated assessment methodologies to air quality plans: two European cases. Environ Sci Pol 65:29–38

Reis S, Nitter S, Friedrich R (2005) Innovative approaches in integrated assessment modelling of European air pollution control strategies–implications of dealing with multi-pollutant multi-effect problems. Environ Model Softw 20:1524–1531

Sjöberg, K., Haeger-Eugensson, M., Forsberg, B., Åström, S., Hellsten, S., Larsson, K., Björk, A. & Blomgren, H (2009) Quantification of population exposure to PM2. 5 and PM10 in Sweden 2005. IVL rapport B, 1792

Thunis P, Degraeuwe B, Pisoni E, Ferrari F, Clappier A (2016a) On the design and assessment of regional air quality plans: the SHERPA approach. J Environ Manag 183(Part 3):952–958

Thunis P, Miranda A, Baldasano JM, Blond N, Douros J, Graff A, Janssen S, Juda-Rezler K, Karvosenoja N, Maffeis G, Martilli A, Rasoloharimahefa M, REAL E, Viaene P, Volta M, White L (2016b) Overview of current regional and local scale air quality modelling practices: assessment and planning tools in the EU. Environ Sci Pol 65:13–21

Vedrenne M, Borge R, Lumbreras J, Rodríguez ME (2014) Advancements in the design and validation of an air pollution integrated assessment model for Spain. Environ Model Softw 57:177–191

Vedrenne M, Borge R, Lumbreras J, Conlan B, Rodríguez ME, De Andrés JM, De La Paz D, Pérez J, Narros A (2015) An integrated assessment of two decades of air pollution policy making in Spain: impacts, costs and improvements. Sci Total Environ 527:351–361

Wagner, F., Amann, M. & Schoepp, W (2007) The GAINS optimization module as of 1 February 2007. IIASA Interim Report IR-07-004, http://www.iiasa.ac.at/Admin/PUB/Documents/IR-07-004.pdf

WHO (2016) Ambient air pollution: a global assessment of exposure and burden of disease. World Health Organization, Geneva

Zachary DS, Drouet L, Leopold U, Reis LA (2011) Trade-offs between energy cost and health impact in a regional coupled energy–air quality model: the LEAQ model. Environ Res Lett 6:024021