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Applying integrated assessment methodologies to air quality plans: Two European cases

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ABSTRACT

Air pollution Integrated Assessment Models (IAM) can be used for determining how emissions should be reduced to improve air quality and to protect human health in a cost-efficient way. The application of IAM is also useful to spread information to the general public and to explain the effectiveness of proposed Air Quality Plans. In this paper, the application of the RIAT+ system to determine suitable abatement measures to improve the air quality at a regional/local level is presented for two European cases: the Brussels Capital Region (Belgium) and the Porto Urban Area (Portugal). Both regions are affected with PM10 or NO_2 concentrations that exceed the limit values specified by the European Union legislation. To properly assess air quality abatement measures a surrogate model was used, allowing the implementation of an efficient optimization procedure. This model is derived in both cases through a set of simulations performed using a Chemistry Transport Model fed with different emission reduction scenarios. In addition, internal costs (due to the implementation of emission reduction measures) and external costs (due to population exposure to air pollutant concentrations) of policy options were considered. The application of this integrated assessment modelling system in scenario (Brussels case) and optimization (Porto) modes contributes to identifying some advantages and limitations of these two approaches and also provides some guidance when urban air quality has to be assessed.

1. Introduction

European Union Member States (EU-MS), in the last decade, have developed urban air quality plans applying a wide range of different modelling methods to assess the effects of local and regional emission abatement policy options on air quality and human health (Borrego et al., 2012; Carnevale et al., 2011; Cuvelier et al., 2007; Lefebvre et al., 2011; Mediavilla-Sahagún and Apsimon, 2003, 2006). In the scope of the APPRAISAL EU FP7 project a review of air quality plans developed by the EU-MS and their assessment practices has been done (Thunis et al., 2016) aiming to identify methodologies and their limitations and to propose possible key areas to be addressed by research and innovation on the basis of this review. A structured online database of methodologies has been developed in collaboration with experts involved in the design of air quality plans (AQP) and Thunis et al. (2016) summarize the main outcomes of this database contents. Current practices vary widely between member-states and between the different administrative levels at which the assessment is undertaken, but there is a general need for more 'integrated' approaches, namely for the use of Integrated Assessment Modelling (IAM), which bring together air quality, health and cost-benefit aspects in the current assessment methodologies for air quality plans.

At the European scale, IAM have been developed in the recent years to provide a technical base for intergovernmental negotiations in a structured way. In the context of the United Nation Economic Commission for Europe (UNECE)'s Convention on Long Range Transboundary Air Pollution (CLRTAP), the integrated assessment model RAINS/GAINS (Wagner et al., 2007) has been extensively used to determine cost-efficient policies to reduce emissions and achieve EU-wide targets for various air quality

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indicators. Furthermore, IAM developed at the European scale, have been adapted to the national scale to be used to optimize emission reductions, e.g. the RAINS-Italy (D'Elia et al., 2009), the RAINS-Netherlands (Aben et al., 2005), the FRES-Finland (Karvosenoja, 2008), or the AERIS (Vedrenne et al., 2015) applied to Spain and Portugal. The USIAM (Mediavilla-Sahagún and Apsimon, 2006), the OTELLO (Comes et al., 2010) and the RIAT+ (Carnevale et al., 2012a) models were specifically developed to address regional and urban areas, but a more extended use of IAM in the scope of AQP would better support policy-makers in their definition of air quality improvement measures.

Aiming to support stakeholders with answers to questions related to the choice of an integrated assessment (IA) modelling tool, its setup and the evaluation of its outputs, a state of the art guidance document on IA applications was prepared in the scope of the APPRAISAL EU FP7 project (APPRAISAL, 2015a). The proposed design for an IAM is focused on the Driver/Pressure/State/Impact/Response (DPSIR) scheme put forward by the European Environment Agency (EEA, 2011) for describing the interactions between society and environment. The DPSIR building blocks were mapped onto the IAM elements as described by Viaene et al. (2016), namely: (i) Driving forces – the key activities that result in pollutant emissions; (ii) Pressures – the pollutant emissions; (iii) State – the air quality; (iv) Impacts – the consequences of the air quality for human exposure and health impacts and for environment; and (v) Responses – the measures that are available to reduce the impacts. The choice of abatement measures (responses) could be the beginning of the process with a clear link to the main activity sectors (drivers) and therefore to related emissions (pressures), which are converted to air quality (state) and finally to impacts.

This guidance was tested by applying an IAM tool to two test cases: one for the Brussels Capital Region in Belgium and the other to the region of Porto in the North of Portugal. This paper aims to present the main results from the application of the guidance recommendations to these two case studies, identifying limitations and future needs.

2. Brussels and Porto case studies

Within IAM two different pathways for identifying the appropriate abatement measures to be taken can be distinguished: (i) expert judgment/source apportionment or scenario analysis, and (ii) optimization approach. The first pathway is mainly used nowadays to design AQP at regional/local scale (Viana et al., 2008; Karagulian and Belis, 2012). Emission reduction measures are selected on the basis of expert judgment 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. In this section, the application of a scenario and an optimization approach is described. The scenario approach was applied to the Brussels case study and the optimization one to the Porto case study. Both case studies are based on the use of the RIAT+ IA system.

2.1. The RIAT+ system

RIAT+ (Carnevale et al., 2014) is an IA tool designed to help regional decision makers select air pollution reduction policies that improve the air quality at minimum costs. Both decision pathways (scenario analysis and optimization) can be selected within RIAT+. Its application to the solution of a decisional problem was based on the scenario approach, for the Brussels Capital Region in Belgium, and on the optimization mode, for the region of Porto in the North of Portugal. For both cases the decisional problem was the cost-efficient improvement of air quality levels to accomplish the 2008 EU Air Quality Directive limit-values.

The main inputs for RIAT+ are the emissions, a database containing details on the emission reduction efficiency, costs of available emission abatement measures (technical and non-technical), and a surrogate model that can calculate the effect of a set of selected abatement measures on an air quality indicator (AQI). The RIAT+ inputs structure can be associated to the DPSIR framework. The emissions database covers the Drivers and Pressures blocks and the surrogate model allows estimating the State in terms of air quality.

The default RIAT+ database with abatement technologies available for different macro-sectors (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 database (Amann et al., 2011) contains activity data for the years 2010, 2015, 2020 and 2025. The year 2010 has been chosen as the reference year for both case studies, which is closest to the year used for the regional emission inventories (2009).

In the measure database, the CLE level (Current Legislation) is the level of application rates (the degree of implementation of a technology) that reflects the requirements of the current legislation. MFR (Maximum Feasible Reduction) is the level of application rates that reflects the maximum physically plausible application degree of a technology. The GAINS database provides for each measure/technology the degree of potential application (potential application rate) used to compute the MFR scenario.

Since the optimization process may require thousands of AQI computations to determine the optimal set of measures needed to reduce an indicator below a given certain level at minimum cost, a Chemical Transport Model (CTM) is not a direct option due to its high computational time. This is why the other important component of the IA system is the surrogate model linking precursor emissions and pollutant concentrations/AQI. This can be as simple as a linear relationship between emission and concentration/AQI or as complex as a non-linear relationship that could better reproduce the non-linearity of secondary pollutants generation. In the case of RIAT+, these non-linear relationships, linking emissions and air quality indices, consist of Artificial Neural Networks (ANN) trained to replicate the results of CTM simulations (Carnevale et al., 2012b). For the surrogate model training phase, a limited set of CTM calculations is performed. This set is representative of the possible emission variability and corresponding concentrations/AQI that can be encountered when applying the IAM. The process of selecting the emission scenarios that should be simulated by a CTM, in order to produce the training data set, is typically referred to as the 'Design of Experiment'. These simulations have to be limited in number due to high computational time of the deterministic model, but they also must be able to represent, as closely as possible, the cause-effect relation between precursor emissions and the various considered AQI.

In this work, for both test cases, non-linear surrogate models based on ANN have been preferred to linear models, since these studies are focused on secondary PM10 concentration reduction, whose generation involves non-linear processes taking place in atmosphere.

The procedure to implement surrogate models requires two steps. Because in the context of neural networks it is impossible to know a priori which ANN structure produces the best results, in the first step the best ANN structures were chosen on the basis of maximum correlation and minimum Root Mean Square Error (RMSE), considering a series of different possible configurations (i.e. different network structure, activation function and number of cells). Then, in a second step the best structure was applied to the whole study domain.

2.2. Brussels scenario approach

The Brussels Capital Region (BCR) has an area of 161 km^2 and is home to more than 1.1 million people. The region consists of 19 municipalities, one of which is the Brussels Municipality, the capital of Belgium. The location of the BCR in Belgium is shown in Fig. 1.

To set up the RIAT+ system for the BCR, the list of possible abatement measures, with their relative costs and effects on emissions, is required. From the onset it was clear that in this case the BCR authorities would only be willing to consider a limited set of possible measures that were deemed politically viable. The default database with measures in RIAT+, which is based on GAINS, was therefore replaced by a database with only ten possible abatement measures consisting of 6 traffic measures and 4 domestic heating measures, all of which have been proposed by the Brussels authorities. Most of the measures are contained in the Plan Air-Climate-Energy proposed by Brussels Environment (Bruxelles Environnement, 2015). These measures have been studied extensively in dedicated studies commissioned by the BCR authorities aiming to properly define their abatement efficiency, as well as other characteristics. Only for the low emission zone (LEZ) the emission reductions are based on the data for the EURO standards, as found in the GAINS database. The emission removal efficiency for the selected measures is listed in Table 1.

To identify the most cost effective measures and use RIAT+ in optimization mode also requires information on the costs for these ten abatement measures. While for most measures cost estimates could be found in the reports provided by the BCR authorities, in general many of these cost estimates were found to be rather disputable. As an example, costs for abatement measures that only required a change in legislation were often deemed negligible in these reports. While it is true that such measures can be implemented without costs for the authorities that impose the measure they do often incur a cost for those that will have to comply with the changes in legislation. As an optimization minimizing costs would then boil down to prioritizing these 'cost free' abatement measures, it was decided to apply the RIAT+ in scenario mode, for the BCR test case, so that the costs of implementing the measures could be neglected.

2.2.1. Design of the experiment and surrogate models

The design of the experiment aims to select the scenarios to be simulated by a CTM, in this case the AURORA model (Lauwaet et al., 2013; Mensink et al., 2001) in order to define the identification and validation dataset for surrogate models.

For the Brussels Capital Region study, AURORA was set up for a domain of 49 $\times$ 49 grid cells at 1 km resolution for the year 2009. For the vertical discretization, 20 layers were used for a domain extending up to 5 km. The layer thickness increases from 27 m for the bottom layer to 743 m for the top layer. For the boundary conditions, the results of an AURORA run for the same year was used for a domain covering Belgium at a resolution of 4 km. These same boundary conditions were used in all runs. For the meteorological inputs, the ECMWF ERA INTERIM data with a resolution of 0.25° were used and interpolated to the model grid. The emissions are based on the EMEP/CORINAIR emission inventory. CORINAIR (Core Inventory of Air Emissions) is a project performed since 1995 by the European Topic Centre on Air Emissions with the aim to collect, maintain, manage and publish information on emissions into the air by means of European air emission inventory and database system (EEA, 2007). The 2009 EMEP/CORINAIR based national emissions for Belgium were spatially disaggregated using the Emission MAPping tool (E-MAP) developed by Maes et al. (2009) to determine grid cell level emissions for the BCR domain.

The air quality results of the 1 km resolution model setup were validated by comparison to the observed values from the European Air quality database (AirBase, http://acm.eionet.europa.eu/databases/airbase/) for the measurement stations inside the model domain. For the validation, the methodology proposed by FAIRMODE (http://fairmode.jrc.ec.europa.eu/) was adopted (Pernigotti et al., 2013; Thunis et al., 2013). More details on the validation and results can be found in APPRAISAL (2015b).

Three levels of emission application were distinguished: base case (B), high emission reductions (H), and low emission reductions (L). The B emission level corresponds to the CLE2020 emissions, increased by 20%. The CLE2020 emissions are by definition the largest emission values that can appear as these correspond to the emissions that are mandated by already adopted legislation. By taking 20% higher emissions for the base case scenario we ensure that the emissions in the scenarios will always be smaller than those of the base case. The H level emissions are obtained by projecting the 2009 regional emission inventory to 2020, and applying the maximal emission reductions. For this, the RIAT+ pre-processor was used taking into account the

Fig. 1. Location of the BCR (red zone) in Belgium.

Table 1
List of measures considered for the BCR with their removal efficiency as% of the 2010 emission, and the yearly average NO_2 and PM_{10} concentration values, and health costs calculated by RIAT+.

	Measures	Emission reduction per compound (%)					NO_2 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)	Health costs (M€)
		NOx	VOC	PM10	PM2.5	SO_2			
0	Reference	0	0	0	0	0	28.6	22.1	334
1	Eco driving	0.62	0.12	2.31	2.43	0	28.6	22.1	333
2	Modal Shift	0.62	0.12	3.47	3.64	0	28.6	22.1	332
3	Transport plan	0.62	0.12	3.47	3.64	0	28.6	22.1	332
4	Urban toll	5.61	1.35	17.36	18.22	0.04	28.2	21.0	317
5	Parking places	0.31	0.06	1.16	1.21	0	28.6	22.1	333
6	Low Emission Zone	2.00	0.20	19.40	17.2	0	28.6	22.0	333
	Σ Traffic	9.78	1.97	47.17	46.34	0.04	27.8	20.7	312
7	Boiler maintenance	2.2	0.19	2.25	2.5	1.51	28.6	22.0	333
8	Exemplary building	0.14	0.01	0.05	0.06	0	28.6	22.1	334
9	Energy efficiency large buildings	0.21	0.02	0.16	0.18	0.08	28.6	22.0	334
10	Energy audits	0.96	0.09	0.54	0.6	0.30	28.6	22.0	333
	Σ Heating	3.51	0.31	3.00	3.34	1.89	28.6	21.9	332
	All	13.29	2.28	50.17	49.68	1.93	27.7	20.6	310

potential technology application rates for 2020 derived from Amann et al. (2013). These are further decreased by 20% in a similar way to what has been done for the B scenario. The 20% increase/decrease of the extreme scenarios is needed in order to avoid border effects that could be generated when the surrogate model simulates scenarios that are too close to these extreme scenarios. Furthermore, since, for this study domain, emission variation between L and H scenarios is limited, a high percentage variation (20%) has been applied. The emissions for the L level (low emission reductions) are then obtained as the average between B and H levels.

In order to determine the emission reduction scenarios for which the CTM is executed, the three levels B, H, L were combined according to expert judgment to produce the 14 emission scenarios listed in Table 2. Scenarios 1 and 3 are the extreme emission scenarios. For scenario 2 emissions are exactly in the middle of the emission range. In the scenarios 4–8 all precursor emissions are at B level, except for one precursor, considering these scenarios allow the surrogate model to reproduce the variations of a single precursor. Finally, scenarios 9–14 represent combined precursor reductions.

One year simulations were performed for the 14 scenario emission inputs described above using the AURORA model (Lauwaet et al., 2013; Mensink et al., 2001). The outputs resulting from the AURORA scenario runs were combined to generate a training dataset for the Artificial Neural Networks (ANN) to be used as a surrogate model in RIAT+. The Air Quality Indices (AQI) that were related to emissions by the ANN were:

Table 2
List of the emission reduction scenarios obtained combining B, H, L scenarios.

Scenarios	NOx	VOC	NH_3	PM10	PM2.5	SO_2
1	B	B	B	B	B	B
2	L	L	L	L	L	L
3	H	H	H	H	H	H
4	H	B	B	B	B	B
5	B	H	B	B	B	B
6	B	B	H	B	B	B
7	B	B	B	H	H	B
8	B	B	B	B	B	H
9	H	H	L	L	L	L
10	H	L	H	H	H	H
11	H	L	H	L	L	L
12	H	L	H	L	L	H
13	L	L	L	L	L	H
14	H	L	H	L	L	H

- PM10: yearly average of PM10 concentrations;
- NO_2: yearly average of NO_2 concentrations.

The process of selecting and training ANN structures was based on the method proposed by Carnevale et al. (2012b). Since, for the computations of the AQI in a grid cell, also the emissions from nearby cells should be taken into account, the emissions surrounding individual model grid cells were summed. Several tests were done to identify the best radius of influence to aggregate them. From these tests, by selecting the radius allowing to train the surrogate model with the higher correlation and lower mean squared error, it was decided to use a 14 cells radius for PM10 and a 20 cells radius for NO_2 for aggregation of emissions.

To validate the results from the ANN, output values were compared to the results calculated by the AURORA model. An independent validation data set, which consists of a random selection of 20% of the grid cells for which the AURORA results were not used in the training of the ANN, was considered. In Fig. 2 these validation results are shown for NO_2 and PM10. The closer the dots are to the bisecting line, the better the surrogate model is able to reproduce AURORA outputs.

As can be seen from these scatter plots (Fig. 2), the ANN is able to reproduce the modelled concentrations for both NO_2 and PM10, although the results for NO_2 are somewhat better.

RIAT+ does not only calculate the concentration changes due to emission changes but also the health costs in terms of morbidity and mortality. To allow RIAT+ to calculate these health costs for the BCR, a 100 m resolution population density map, provided by the Ministry of internal affairs, was resampled to the 1 km resolution model grid.

2.2.2. Results obtained with RIAT+

Once the ANN have been trained, they can be used to obtain results for the different scenarios. RIAT+ can produce both tabular output and maps for the emissions, the AQI and derived quantities such as the years of life lost (YOLL) for the health costs. Fig. 3 shows the spatial distribution of the YOLL, as visualised by RIAT+, for CLE2020, and considering the implementation of all proposed traffic and non-industrial heating measures. Table 1 presents for each measure considered the areal average NO_2 and PM_{10} concentrations as well as the health costs.

The spatial distribution of the YOLL values (Fig. 3) indicates higher health effects, in terms of years of life lost, in the north-western part of the domain, where both concentrations and population density are highest.

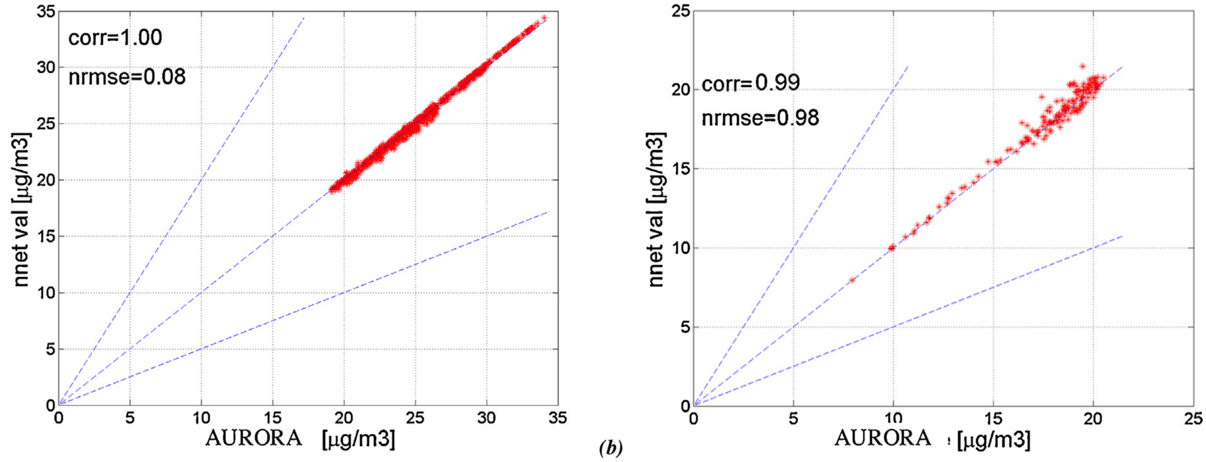

Fig. 2. NO_2 (a) and PM10 (b) scatter plots for the validation of the ANN outputs vs AURORA outputs.

From Table 1 it can be seen that the yearly average NO_2 and PM10 concentration will decrease, respectively, by 0.9 $\mu g/m^3$ (4%) and 1.5 $\mu g/m^3$ (7%), on average, when all the proposed traffic and all non-industrial heating measures are applied and that this will reduce the health cost by 24 M€/year (7%) in the BCR. Looking at individual measures, the 'Urban toll' measure seems most effective. The LEZ measure has less effect than could be expected based on its emission reductions as listed in Table 1. This is due to the fact that in 2020 a large part of the vehicles of type EURO 1–EURO 4 will already have been replaced by newer types in the CLE2020 case. While one could point out that the current resolution of 1 km is still too coarse to assess street level air quality and that the effect of the proposed abatement measures could in fact be larger, the RIAT+ results indicate that the impact of the selected abatement measures on air quality will be limited. This is due to both the small number of abatement measures considered and the size of the study domain and illustrates the limitations of local policies, as the Brussels authorities can only impose measures on emissions that are within their jurisdiction.

2.3. Porto optimization approach

The Great Porto Area is a Portuguese NUTS3 (Nomenclature of Territorial Units for Statistics) sub region involving

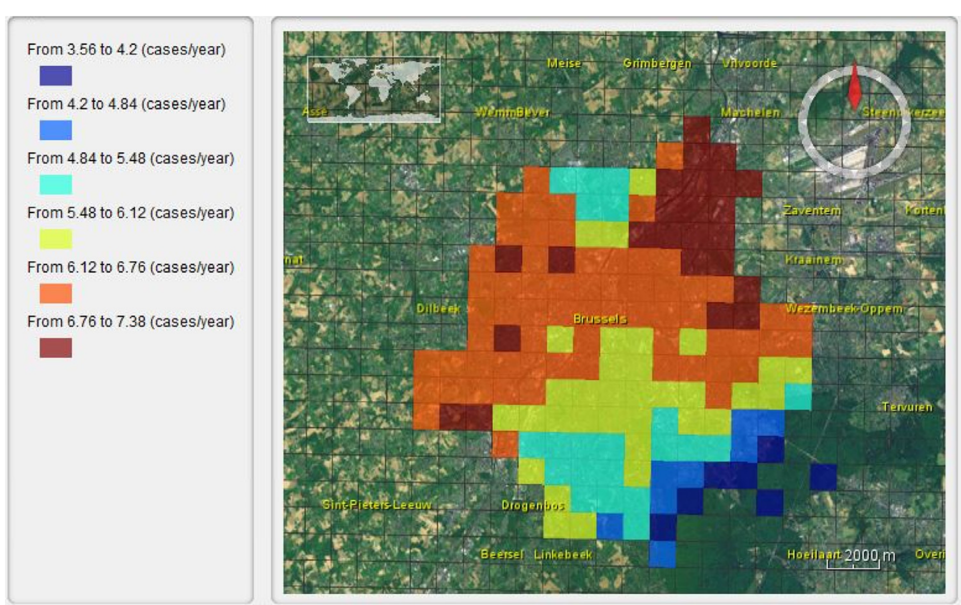

Fig. 3. Years of life lost (YOLL) in 2020 when all proposed traffic and non-industrial heating measures are implemented. (The reader is referred to the web site version of this article for a figure with colours.)

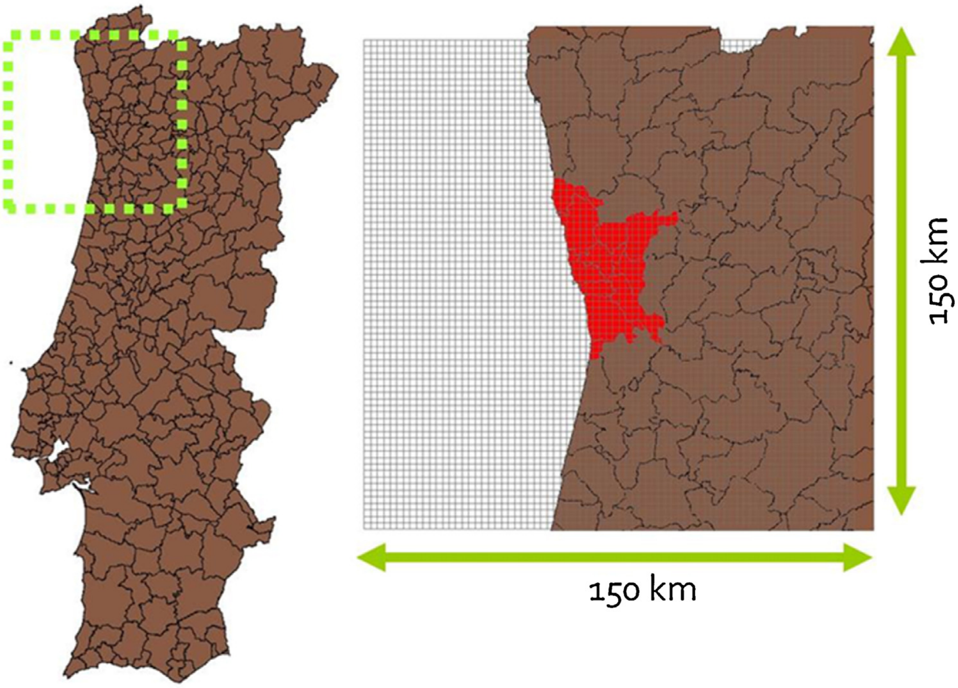

Fig. 4. Location of the Great Porto Area in Portugal and in the Northern Region of Portugal. (The reader is referred to the web version of this article for a coloured figure.)

11 municipalities. It covers a total area of 1024 km^2 with a total population of more than 1.2 million inhabitants. Population data by age groups and per municipality were extracted from the National Statistical Institute database (INE, 2012) and were used to calculate population exposure to PM10.

Fig. 4 shows the location of the Greater Porto Area in Portugal and in the northern region of Portugal.

This region of Portugal is one of the several EU zones that had to develop and implement AQP to reduce PM10. Air Quality Plans were initially designed based on a scenario approach using the TAPM air quality model. The model was applied over the study region for the reference situation with the current PM10 emissions, and for a reduction scenario with PM10 emissions re-estimated considering the implementation of abatement measures (Borrego et al., 2011; Borrego et al., 2012). The most relevant identified emission sectors were industrial combustion, residential combustion and road traffic. Vedrenne et al. (2015) describe the application of the Atmospheric Evaluation and Research Integrated model for Spain (AERIS) to the Iberian Peninsula, providing decision and policy making support for different "what-if" scenarios, but not proposing a specific list of optimal measures. The RIAT+ tool is now applied in the optimization mode aiming to contribute to a better definition of air quality improvement measures.

Similarly to the Brussels case study, to set up the RIAT+ for the Great Porto Area, a list of abatement measures, including costs and emissions effects, is required. The GAINS database (http://www.iiasa.ac.at), which contains a large data set collected for Portugal, was used. The most relevant local measures proposed in the Porto's AQP were identified in the GAINS-Portugal measures database, namely: new/improved fireplaces (SNAP2), efficient dedusters (SNAP3 and SNAP4), and low-emission vehicles (SNAP7). Moreover, other technical measures included in the GAINS-Portugal database were reviewed and selected, amounting to 130, in order to be used in the Greater Porto Area according to its main characteristics and needs.

2.3.1. Design of the experiment and surrogate models

Starting from the 2009 Portuguese emission inventory, three different emission levels were also considered to establish scenarios inside the Great Porto Area (Policy Application Domain – PAD): B (base case), L (low emission reductions) and H (high emission reductions). The B (base) case considers the evolution of 2009 emissions taking into account the fulfilment of the CLE2020 scenario, derived from Amann et al. (2013), increased by 15% (upper bound) to enlarge the identification bounds for Artificial Neural Networks and therefore guaranteeing the correct identification of surrogate models. The H (high reduction) case is associated to the Maximum Feasible Reduction of emissions at 2020 (MFR2020), decreased by 15% (lower bound). The MFR2020 emissions were estimated using rescaling factors, derived also from Amann et al. (2013), and applied to the 2020CLE projected emissions. Since the considered emission range is wider than the Brussels case, a lower percentage (15%) can be considered to widen the range between the emission scenarios. The L (low reduction) scenario results, as previously mentioned for the Brussels case study, from averaging B and H emission scenarios values. Outside the PAD, emissions were

Table 3
List of the emission reduction scenarios obtained combining B, H, L scenarios.

Scenarios	NO_X	VOC	PM10	PM2.5	SO_2
0	B	B	B	B	B
1	L	L	L	L	L
2	H	H	H	H	H
3	H	L	L	L	L
4	L	H	L	L	L
5	L	L	H	H	L
6	L	L	L	L	H
7	H	H	L	L	L
8	H	L	H	H	H
9	H	L	L	L	H

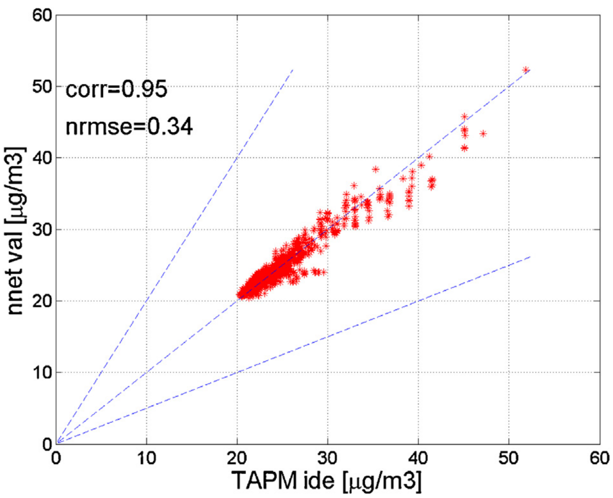

Fig. 5. ANN system performance evaluated in terms of scatter plot between ANN and TAPM results for PM10.

considered fixed at Current Legislation Emissions at 2020 (CLE2020) level.

Due to computational time constraints, the minimum set of scenarios needed to train RIAT+ Artificial Neural Networks was the basis for the modelling activities. This minimum number of scenarios has to reproduce all the possible precursor emissions variations. Table 3 presents the list of used reduction scenarios to train the RIAT+ Artificial Neural Networks for the Great Porto Area. The idea behind the selection of these scenarios is the same presented for Brussels test case, but Table has been modified considering the different features of the CTM applied for the simulations (in this case not considering NH_3 emissions).

The Air Pollution Model (TAPM) (Hurley et al., 2005), which incorporates a meteorological model, was used for the simulation of the different reduction scenarios. The model was applied for one entire reference year, with a 2 km by 2 km spatial resolution, with 25 vertical grid layers. Boundary conditions are coming from the application of this model to the Iberian Peninsula (one-way nesting). The Portuguese emission inventory for 2009 (the most up to date available one), by pollutant and activity sector, was spatially and temporally disaggregated to obtain the resolution required for the TAPM application.

Modelled concentrations by TAPM were compared against measurements from the Portuguese Agency for the Environment (APA) 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 (2015b).

The TAPM simulations for the 10 reduction scenarios were the basis for the ANN training and validation data series. The target (Air Quality Index) considered was the PM10 annual average. Fig. 5 presents the ANNs performance for the annual PM10 concentration value.

The scatter plot (Fig. 5) shows the good performance of the ANN, with a Normalised Root Mean Square Error (RMSE) of 0.35 and a correlation coefficient of 0.95, and confirms that ANN has the capability to simulate the nonlinear source–receptor relationship between PM10 mean concentration and the emission of its precursors.

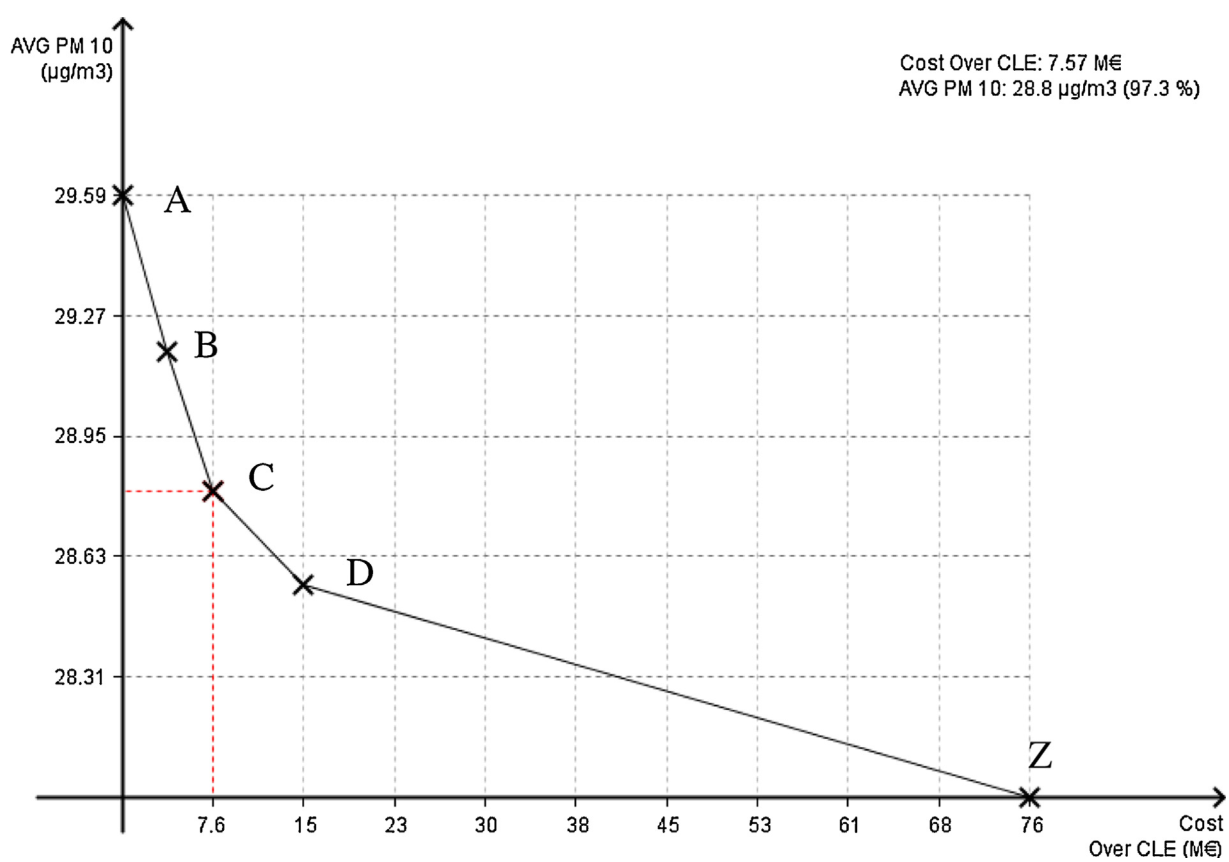

Fig. 6. Pareto curve for the optimization of PM10 yearly mean concentrations.

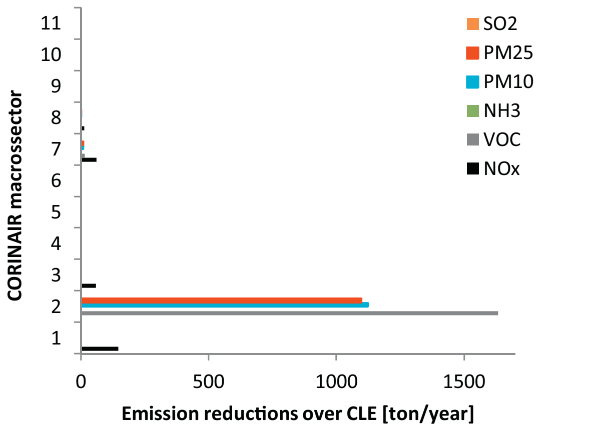

Fig. 7. RIAT+ emission reductions per precursor (ton/year), by EMEP/CORINAIR macro-sector corresponding to point C of the Pareto curve. (The reader is referred to the web version of this article for a coloured figure.)

2.3.2. Results obtained with RIAT+

RIAT+ was applied in the Multi-objective optimization mode and Fig. 6 shows the solutions over the Great Porto domain. On the horizontal axis of the figure there are internal costs, considered over CLE and expressed in Millions of Euros, and on the vertical axis there is the averaged AQI value (for this particular case, PM10 annual average) estimated for the entire study area.

The Pareto Curve (a curve providing the optimal solutions ranked by costs) shows that a PM10 mean concentration of 28.8 μg. m^3 can be reached adopting emission reduction technologies costing around 7.6 Million Euros per year (point C). While points A and Z represent extreme cases, no actions or maximum effective reductions, respectively, are implemented, the other points of the Pareto Curve are intermediate solutions (possible combinations of reduction measures and their cost and AQI).

For the point C of the Pareto Curve, Fig. 7 presents the emission reduction by EMEP/CORINAIR macro-sector and for the different considered precursors. PM concentration reductions, for point C, would be reached mainly acting on non-industrial sector activities (SNAP 2), targetting primary PM emissions as well as Volatile

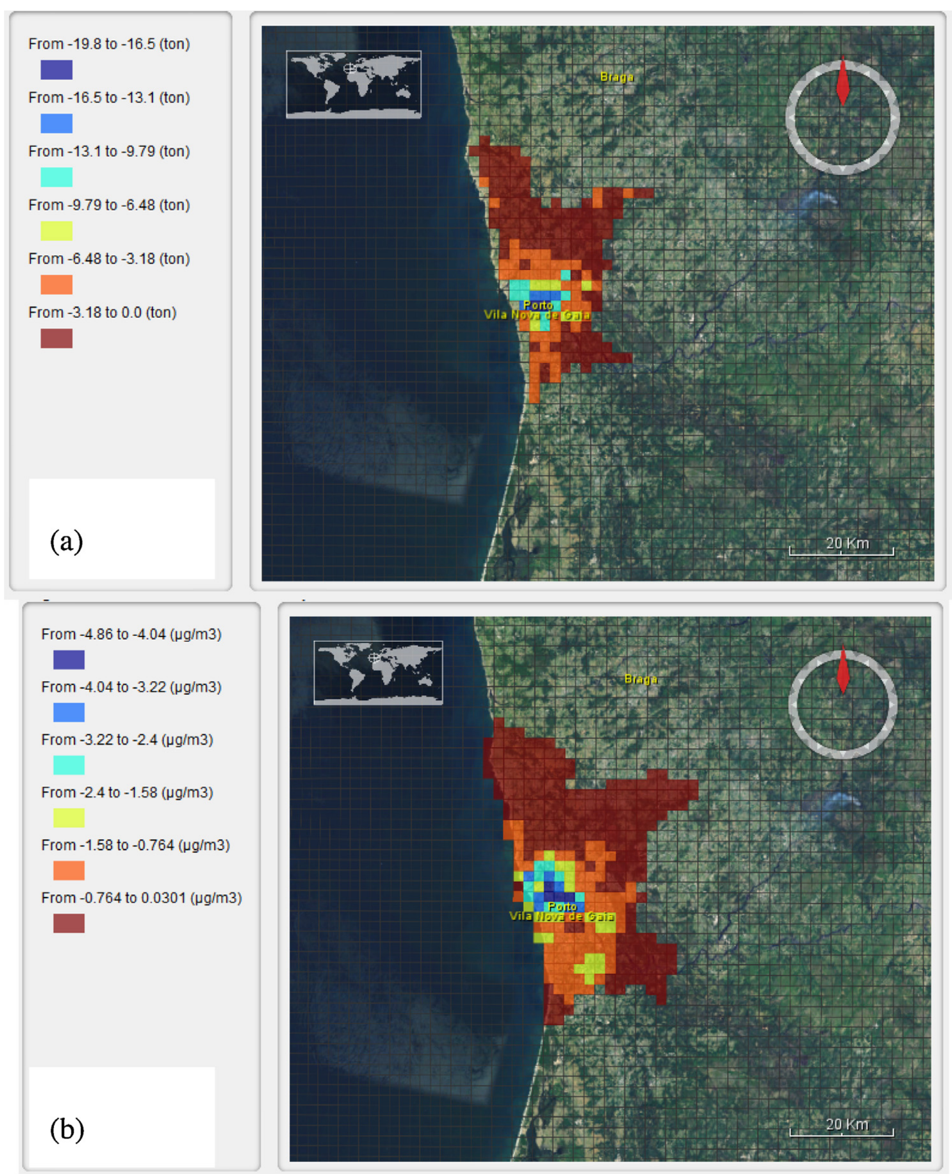

Fig. 8. RIAT+ emission (ton/year) (a) and concentration ($\mu g\, m^{-3}$) (b) reductions for the point C of the Pareto curve. (The reader is referred to the web version of this article for a coloured figure.)

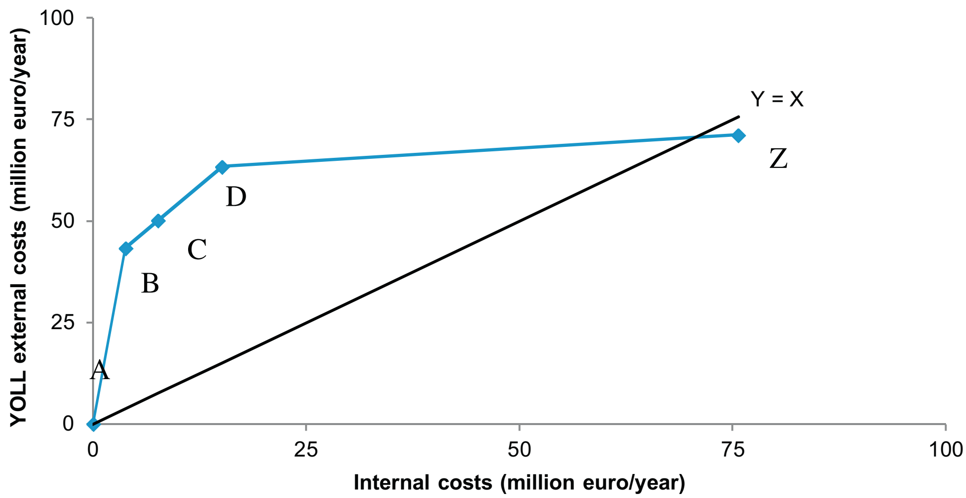

Fig. 9. YOLL external costs vs internal costs (million euro per year).

Organic Compounds (VOC). Road transport (SNAP 7) and other mobile sources and machinery (SNAP 8) could also contribute to this reduction of PM concentrations. As shown in Fig. 7 it is also possible to reduce PM concentration values via reduction of NOx emissions acting on energy industries (SNAP 1) and combustion in manufacturing industry (SNAP 3) sectors.

According to Borrego et al. (2012) in Portugal 18% of PM10 emissions are due to residential wood combustion, which may deeply impact the PM10 levels in the atmosphere, and according to the Portuguese emission inventory this macro-sector is the second most important in terms of PM10 emissions, after macro-sector 4 (industrial processes), in the Great Porto Urban area.

Fig. 8 presents the spatial distribution of the expected reductions of PM10 emissions and concentration levels, for the Point C of the Pareto curve. Based on this optimized emission reduction scenario represented by Point C, larger reductions of PM10 concentration levels (up to 4.8 $\mu g/m^3$) are expected over the Porto municipality where the population density is higher.

Finally, Fig. 9 presents the relation between internal and external (or estimated health benefits) costs as calculated by the optimization process. The ratio between external and internal costs significantly decreases when Point B is reached. For this particular case application, such scenario can be marked as optimal in terms of health benefit – measures costs.

As shown in Fig. 9 the external costs are always higher than the internal costs. This fact points out that, acting on emission control to reduce PM10 concentrations is greatly beneficial from a socio-economic point of view.

3. Conclusion

In this document we have presented the implementation of an existing comprehensive IA system (RIAT+) for two different test cases, the Porto Region and Brussels Capital Region. The main conclusions we can draw from the setup and implementation of both test cases are:

- The applications demonstrate that there are tools which can be practically applied in an integrated assessment of air quality that does not only consider compliance of concentration to limit values, but also efficiently takes into account internal and external costs of different available abatement options.
- The biggest task when implementing such a comprehensive IA is – as it is also the case in regular air quality modelling applications – to obtain high quality input data, *i.e.* information on local emissions and the cost and effectiveness of possible abatement measures. When such data is lacking, you can still rely on existing European inventories and databases with data on abatement measures such as EMEP/CORINAIR and GAINS, keeping in mind the assumed validity of such data for the region of interest and the implications for the results obtained using the IAM.
- If an IAM uses surrogate models to relate emission changes to concentration changes, such relationships should be carefully tested to ensure that they not only correctly replicate the concentration values obtained through more complex modelling tools (e.g. CTMs), but also capture the dynamics i.e. the concentration changes calculated by the model for which they are a surrogate.

The application for Brussels showed that in practice, the list of options for abatement measures is restricted not only by what is technically and economically feasible, but possibly even more by political and social acceptance. IA tools should therefore be extended to allow their users to take into account the implications of political and social acceptance in an early stage of the decision process.

In the Brussels case, a lot of time was put into estimating precisely the efficiency of measures while the impact on air quality of these measures is rather limited due to the dimension of the area selected. A first screening step such as a simple scenario to check the importance of the impacts should be done before using a complex methodology as the latter has limited added value in such cases.

In the Porto case, RIAT+ applied in the optimization mode allowed to have a first idea of the optimal investment costs and benefits, in relation to an improvement in PM10 air concentration levels. These costs and benefits are based on a selection of abatement measures coming from the GAINS-Portugal database. The inclusion of behavioural measures would have been an added value for this Porto case.

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