Universidade de Aveiro Departamento de Ambiente e Ordenamento
2018

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Modelos de avaliação integrada para melhorar a qualidade do ar urbano

Integrated assessment models to improve urban air quality

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Ciências e Engenharia do Ambiente, realizada sob a orientação científica da Doutora Ana Isabel Miranda, Professora Catedrática do Departamento de Ambiente e Ordenamento da Universidade de Aveiro.

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palavras-chave

Qualidade do ar; Áreas urbanas; Modelos de avalição integrada; Cenários de redução de emissões; Redes neuronais artificiais; Optimização; Análise multicritério

resumo

Atualmente a poluição atmosférica representa uma das principais causas ambientais de mortalidade. Ela é ainda responsável pela redução da esperança média de vida, redução da produtividade devido à redução de dias de trabalho, aumento de custos hospitalares, e por impactos económicos consideráveis. Os poluentes mais relevantes em termos de efeitos na saúde humana são o material particulado, o dióxido de azoto e o ozono troposférico. O objetivo principal da presente tese é o desenvolvimento e teste de um Modelo de Avaliação Integrada (MAI) que permita apoiar a seleção custo-eficiente de medidas de melhoria de qualidade do ar em cidades. Com essa finalidade foi efetuada uma revisão das atuais metodologias de avaliação integrada da qualidade do ar, das mais simples (análise de cenário) às mais complexas (abordagem de otimização), e foram efetuados alguns testes de aplicação que permitiram identificar as principais vantagens e limitações de cada abordagem. Foi desenvolvido um Modelo de Avaliação Integrada à Escala Urbana (MAIEU) que ultrapassa algumas das dificuldades das ferramentas existentes e aproveita as suas vantagens. O modelo foi avaliado através da sua aplicação a um caso de estudo urbano (Grande Porto) e a diferentes cenários de emissões. É capaz de reproduzir rapidamente cenários de redução de emissões, e de estimar os seus impactes na saúde, recorrendo a Redes Neuronais Artificiais. Para além disso, o uso de Análise Multicritério permitiu incluir aspetos sociais e criar uma classificação de medidas/cenários de qualidade do ar. Este trabalho contribui para uma melhor compreensão da utilidade dos MAI, disponíveis para apoiar o processo de tomada de decisão. O MAIEU, revelou ser útil para avaliar rapidamente o efeito de políticas regionais e locais focadas na melhoria da poluição atmosférica à escala urbana.

keywords

Air quality; Urban areas; Integrated assessment modelling; Emission reduction scenarios; Artificial neural networks; Optimization; Multi-criteria analysis

abstract

Currently, air pollution represents one of the main environmental causes of mortality. It is also responsible by cutting lives short, reducing productivity through working days lost across the economy, increasing medical costs, and by considerable economic impacts. Europe's most serious air pollutants in terms of harm to human health are particulate matter, nitrogen dioxide and ground-level ozone. The principal objective of this thesis is to explore the capabilities of Integrated Assessment Modelling tools to cost-efficiently evaluate measures to improve the air quality, and furthermore to develop an urban Integrated Assessment Model (IAM). For this purpose a review of current integrated assessment methodologies to improve air quality, from simple (e.g. scenario approach) to more comprehensive ones (e.g. optimization approach) was done and some application tests were performed. Based on identified advantages of the revised approaches the Integrated Urban Air Pollution Assessment Model (IUAPAM) was designed and evaluated through its application to a selected urban case study (Porto Urban Area) considering different emission scenarios. The developed model is able to reproduce rapidly emission reduction scenarios and to estimate health impacts, making use of Artificial Neural Networks. Moreover, the use of Multi-Criteria Decision Analysis (MCDA) allows including social aspects and ranking air quality measures/scenarios.

This research work contributes to a better understanding of the utility of IAM tools that are available to support the air quality decision-making process. IUPAM revealed to be useful to quickly evaluate the effect of local and regional policies focused on air pollution improvement.

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List of Abbreviations and Symbols

ACS	American Cancer Society
ANN	Artificial Neural Networks
AFN	Autoridade Florestal Nacional
AOT40	Accumulated exposure over a threshold of 40 parts per billion
APA	Portuguese Environment Agency
AQI	Air Quality Index
AQP	Air Quality Plans
B	Base
BCR	Brussels Capital Region
BOM	Bureau of Meteorology
CCDR-N	Northern Portugal Regional Coordination and Development Commission
CESAM	Associate Laboratory of the University of Aveiro
CLC	Corine Land Cover
CLE	Current Legislation Emissions
CLRTAP	Convention on Long Range Transboundary Air Pollution
CORINAIR	Core Inventory of Air Emissions
COPD	Chronic Obstructive Pulmonary Disease
CPU	Central Processing Unit
CR	Concentration-Response
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTM	Chemical Transport Model
DALY	Disease-Adjusted Life Years
DGEG	Directorate General for Energy and Geology
DPSIR	Drivers – Pressures – State – Impacts – Responses
EEA	European Environment Agency
EIONET	European Environment Information and Observation Network
ERF	Exposure-Response Function
EROS	Earth Resources Observation Systems
EU	European Union
GASP	Global Analysis and Prediction
GEMAC	Research Group on Emissions Modelling and Climate Change
GHG	Greenhouse Gases
GRS	Generic Reaction Set
H	High reduction
HIA	Health Impact Assessment
HRAPIE	Health Risks of Air Pollution in Europe

IA	Integrated Assessment
IAM	Integrated Assessment Modelling
IARC	International Agency for Research on Cancer
IES	Integrated Environmental Systems
IIASA	International Institute for Applied Systems Analysis
INE	Instituto Nacional de Estatística
IUAPAM	Integrated Urban Air Pollution Assessment Model
L	Low reduction
LAPS	Limited Area Prediction System
LEZ	Low Emission Zone
LV	Limit Value
MCDA	Multi-Criteria Decision Analysis
MDS	Model Documentation System
MFR	Maximum Feasible Reduction
NCAR	National Centre for Atmospheric Research
NECD	National Emission Ceilings Directive
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NO_2	Nitrogen Dioxide
NOx	Nitrogen Oxides
NUTS	Nomenclature of Territorial Units for Statistics
O_3	Ozone
PAD	Policy Application Domain
PM	Particulate Matter
PM10	Particulate matter with an equivalent aerodynamic diameter of less than 10 μm
PM2.5	Particulate matter with an equivalent aerodynamic diameter of less than 2.5 μm
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
QALY	Quality-Adjusted Life Years
RIAT	Regional Integrated Assessment Modelling Tool
RMSE	Root Mean Square Error
RR	Relative Risk
SCI	Science Citation Index
SNAP	Selected Nomenclature for Air Pollution
SOMO 35	The Sum of Ozone Means Over 35 ppb
SOx	Sulfur Oxides
TAPM	The Air Pollution Model
TREM	Transport Emission Model for Line Sources
UNECE	United Nation Economic Commission for Europe

URL	Uniform Resource Locator
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
WHO	World Health Organization
YLD	Years With the Disease
YOLL	Years Of Life Lost

1 General Introduction

This chapter discusses air pollution as a health and environmental problem mainly focusing on its impacts in urban areas. It analyses the legal framework, and provides an overview of available modelling tools and air quality management activities.

1.1 Air quality in Europe

Air pollution is defined by the World Health Organization (WHO) as “the contamination of the indoor or outdoor environment by any chemical, physical, or biological agent that modifies the natural characteristics of the atmosphere”. The state of air pollution is often expressed as air quality.

Urban growth, the industrial revolution (middle of the XVII century) and the development of the current transportation systems (XX century) have caused problems of air pollution. The relevance of air pollution impacts was clear, when in 1952 the London Fog resulted in thousands of deaths and health injuries.

Nowadays, nitrogen dioxide (NO_2), tropospheric ozone (O_3) and particulate matter (PM), in particular the ones with an aerodynamic equivalent diameter less than 2.5 µm (PM2.5), are strongly affecting human health and are associated with increased mortality and morbidity (WHO, 2013a). Ambient air pollution kills about 3 million people annually and is affecting all regions of the world, although Western Pacific and South East Asia are the most affected (WHO, 2016). The biggest urban areas around the word are the most affected by air pollution, in both developed and developing countries (Baldasano *et al.*, 2003; Gurjar *et al.*, 2010; Zhang *et al.*, 2016). High pollutants concentrations also impact: i) ecosystems, vegetation grow, biodiversity, etc. (e.g. Emberson *et al.*, 2001); ii) buildings and monuments (e.g. Barca *et al.*, 2014; Di Turo *et al.*, 2016); iii) climate change (e.g. Seinfeld & Pandis, 2016); and iv) visibility (e.g. Wu *et al.*, 2005).

To improve air quality is a complex challenge that requires setting air quality standards, controlling pollutant sources, implementing legislative as well as non-legislative measures that have to be effective. It also requires coordinated efforts at national, regional and local level. According with the 7th Environmental Action Programme (EU, 2013) the overall European Union (EU) air policy strategy is directed towards meeting the Air Quality Guideline Values of the World Health Organization in the coming decades. At the EU level, three main instruments can be distinguished (EU, 2017):

i. The Ambient Air Quality Directives: These Directives (i.e. 2008/50/EC and 2004/107/EC) set air quality standards and requirements to ensure that Member States adequately monitor and/or assess air quality on their territory, in an harmonized and comparable manner. This includes limit concentrations values for twelve key air pollutants. Table 1.1 summarizes the air quality limit and target values defined in the Directive 2008/50/EC, and also the WHO air quality guidelines (WHO, 2006) for the pollutants deemed to be most relevant.

ii. The National Emission Ceilings Directive (NECD): This Directive (i.e. 2016/2284/EC) requires national emission inventories and sets national emission reduction targets to limit transboundary pollution for the most important transboundary air pollutants (non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), sulfur oxides (Sox), ammonia (NH_3) and PM2.5.

iii. Source-specific regulatory approaches: These include e.g. emission limits for vehicles (EURO standards) and non-road mobile machinery, fuel standards, energy efficiency standards, the Industrial Emissions Directive, the Medium-sized Combustion Plants Directive, the Eco-design directive (includes solid fuel boilers and fireplaces), the Sulphur Directive, and the Directive on Deployment of Alternative Fuels Infrastructure.

EU limit values are informed by guidelines set by the WHO, which are not legally binding criteria but they are intended to be relevant to support a broad range of policy options for air quality management in EU. However, as in the case of PM10 and PM2.5, the limits are considerably higher (i.e. less stringent) than the WHO recommendations.The WHO has started in 2016 the revision process of the air quality guidelines for outdoor air pollution, which will provide up-to-date recommendations on ambient pollutant concentrations in order to support policy-makers and protect public health.

Table 1.1 - European air quality standards (EC, 2008) and WHO air quality guidelines to human health protection (WHO, 2006).

Pollutant	**Period**	**EU/ WHO**	**Limit or target value**		**Long-term objective**		**Info. or alert thresholds**	
			Value* *(µg/m^3)	***Exceedances***	***Value***	***Date***	***Period***	***Threshold***
O_3	Max. 8h	EU	120[1]	25 in 3 years	120 µg/m^3		1h	180[2] µg/m^3
							3h	240[3] µg/m^3
	Max. 8h	WHO	100					
NO_X	Calendar year	EU	30					
NO_2	Hour	EU	200	18			3h	400 µg/m^3
	Year		40					
	Hour	WHO	200					
	Year		40					
SO_2	Hour	EU	350	24			3h	500 µg/m^3
	Day		125	3				
	10 min	WHO	500					
	Day		20					
PM10	Day	EU	50	35				
	Year		40					
	Day	WHO	50					
	Year		20					
PM2.5	Year	EU	25 20 (ECO)[4]		8.5 to18 µg/m^3	2020		
	Day	WHO	25					
	Year		10					

Aiming to protect human health from the effects of air pollution the European Union has made important efforts for the reduction of anthropogenic emissions during the last decades. Figure 1.1 shows the air pollutants emission trends in EU-28 (left) and Portugal (right) between 1990 and 2015.

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[1] This is a target and not a legally limit value.

[2] This is an information threshold.

[3] This is an alert threshold.

[4] ECO: The exposure concentration obligation for PM2.5 is fixed on the basis of the average exposure indicator, with the aim of reducing harmful effects on human health. The range for the long-term objective (between 8.5 and 18) indicates that the value depends on the initial concentrations across various Member States.

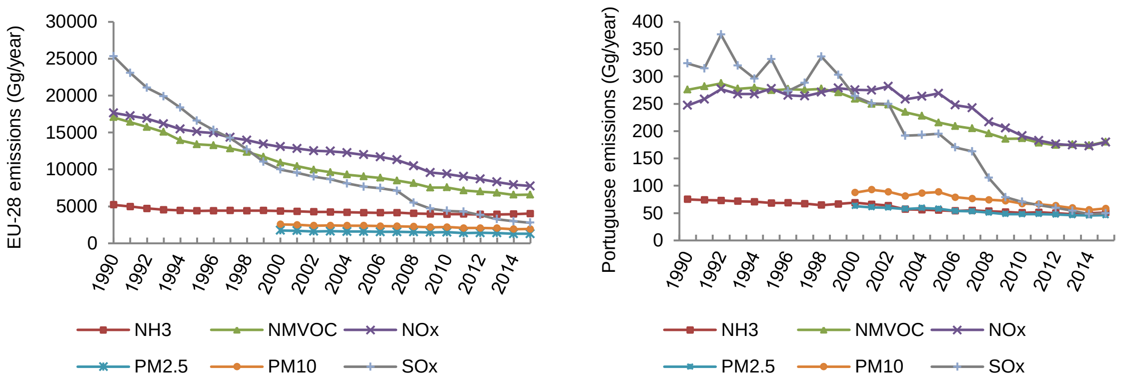


Figure 1.1 - Air pollutants emission trends in EU-28 (left) and Portugal (right) between 1990 and 2015, in gigagrams per year (Gg/year) (Source: adapted from URL1).

It is possible to realize that two key pollutants responsible for the formation of ground-level O_3, NMVOC and NOx have fallen 56 %, and 61 %, respectively, between 2000 and 2015 in the EU-28. The smallest reduction was for NH_3 (23%) and the largest was for Sox (89%). Emissions of primary particulate matter with an aerodynamic equivalent diameter less than 10 µm (PM10) and PM2.5 have fallen by 24 %, and 26 % respectively (EEA, 2017). As for Europe, the main Portuguese emission reduction (Figure 1.1, right) has been reported for SO_X (85%). Moreover, NMVOC (35%), PM2.5 (33%), NH_3 (32%), NOx (27%), and PM10 (27%) also have fallen between 1990 and 2015 (APA, 2017). However, in 2014 the continuous decreasing tendency stopped, and a slight increase of emissions was verified in 2015 for the majority of the pollutants. In Figure 1.2 can be observed the share of EU-28 emissions in 2015, for the main gas pollutants (NO_X, NMVOC, NH_3 and SO_X), and particulate matter (PM10, PM2.5), per activity sector.

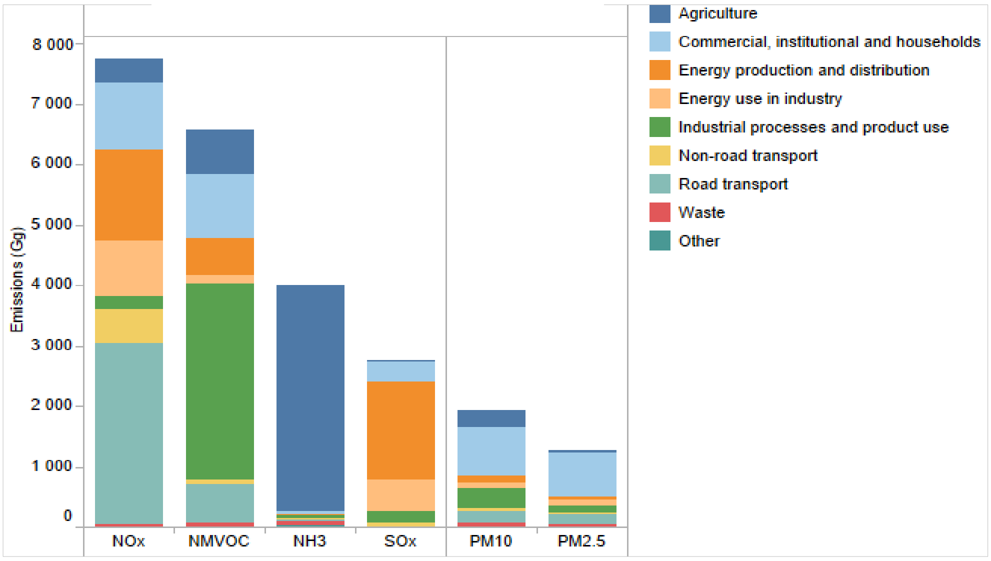


Figure 1.2 - Share of EU-28 emissions of the main pollutants, by sector group in 2015 (Source: adapted from URL1).

The road transport sector was the largest source of NOx emissions (39 % in the EU-28) in 2015, followed by the energy production and distribution, and by the commercial, institutional and households sector. NOx emissions from petrol cars in the EU have decreased considerably since 2000, in line with the increasingly stringent emissions limits. In contrast, NOx emissions from diesel cars have not improved much over the same period, meaning that reductions have not been as large as planned in legislation. In addition, until the EURO 6 regulations came into force, diesel cars were permitted to emit three times as much NOx as petrol cars (EEA, 2016; 2017).

The industrial processes and product use sector (mainly from solvents industry) was the largest contributor to total emissions of NMVOC (50%), followed by commercial, institutional and households (16%), and agriculture (11%). The agricultural sector contributes to 94 % of NH_3 emissions. It is confirmed that NH_3 emissions from agriculture contribute to episodes of high PM concentrations experienced across certain regions of Europe (Erisman & Schaap, 2004; Putaud *et al.*, 2010). NH_3 emissions contribute, therefore, to negative short- and long-term impacts on human health (Lelieveld *et al.*, 2015). Measures such as covering liquid manure storage facilities, or application techniques of manure on soils (injecting instead of spraying can decrease NH_3 emissions substantially (EEA, 2017).

The energy production and distribution sector comprises emissions from a number of activities that employ fuel combustion to produce energy products and electricity, for instance. It is an important source of many pollutants, especially SOx. Despite considerable past SOx reductions, this sector contributes 59 % of the total EU-28 emissions of this pollutant. Several measures have been introduced to reduce SOx emissions, since 1990, like switching fuel in energy-related sectors away from high-sulphur solid and liquid fuels to natural gas (EEA, 2017).

The commercial, institutional and households sector group was a major source of PM2.5 (57%), and also of PM10 (42%). In the case of PM2.5 the second sector more relevant is the road transport sector, whereas industrial processes and product use is more relevant for PM10. The use of wood and other biomass combustion for household heating is growing in some countries, owing to government incentives/subsidies, rising costs of other energy sources, and an increased public perception that it is a “green” option (EEA, 2016). According to the European Environment Agency (EEA) there are four main reasons for the relatively high air pollutant emissions from residential wood combustion: i) use of non-regulated stoves; ii) combustion under non-optimal conditions; iii) inadequate maintenance; iv) use of non-standardized biomass (including treated, painted or insufficiently dried wood, or even agricultural waste).

In Portugal the share of emissions by sector group in 2015 is almost identical to the European average. The emission sectors mentioned above can be classified according to the Selected Nomenclature for Air Pollution (SNAP) categories: public power stations (SNAP 1); commercial and residential combustion (SNAP 2); industrial combustion (SNAP 3); production processes (SNAP 4);

extraction and distribution of fossil fuels and geothermal energy (SNAP 5); solvent and other product use (SNAP 6); road transport (SNAP 7); other mobile sources and machinery (SNAP 8); waste treatment and disposal (SNAP 9), agriculture (SNAP 10), and nature emissions (SNAP 11).

Despite the improvements and reductions verified in emissions, ambient air concentration levels of the main air pollutants (PM, NO_2, O_3) are still high. Figure 1.3 shows the concentration levels in 2015 for the three pollutants across Europe.

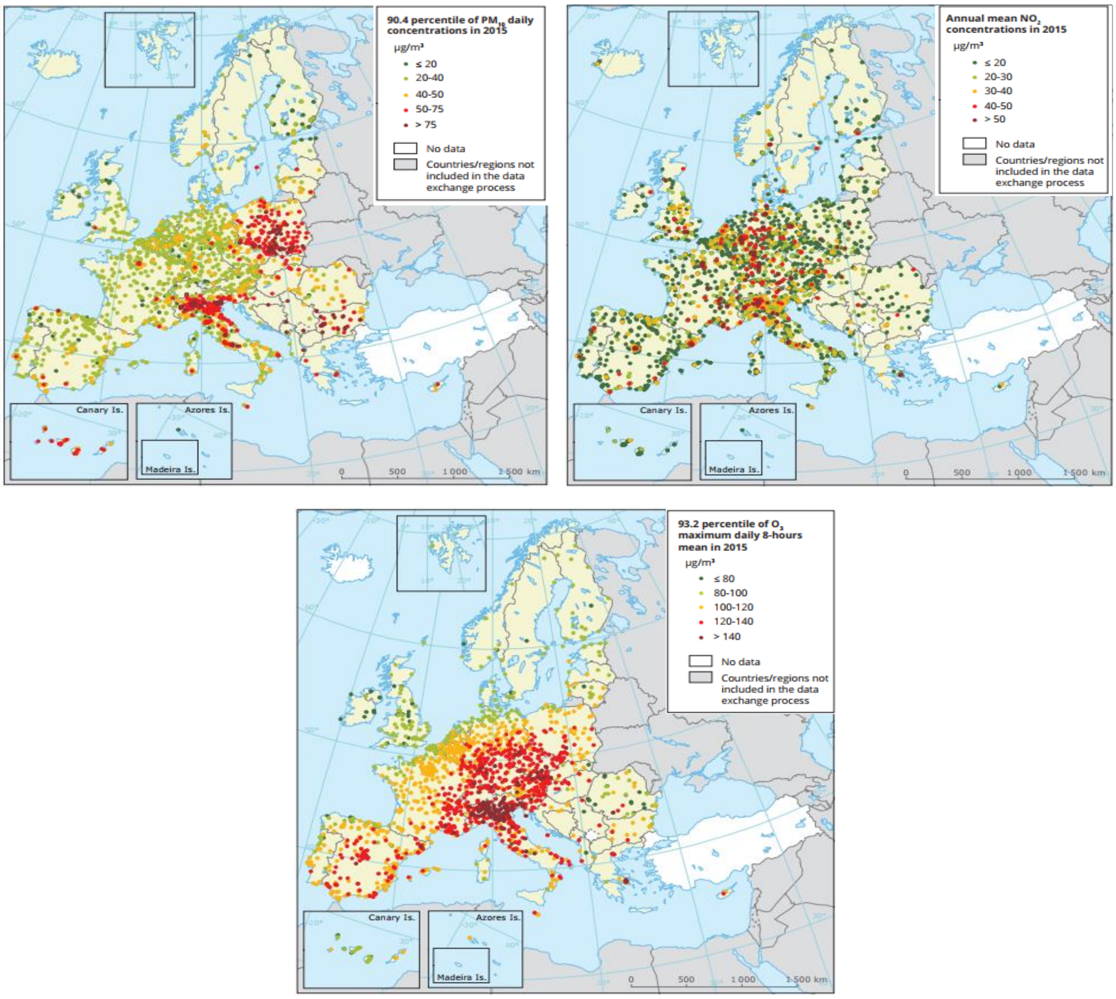


Figure 1.3 - The 90.4 percentile of the PM10 daily mean concentrations (left) and annual mean NO_2 (right) concentrations in 2015; 93.2 percentile of the O_3 maximum daily 8-hour mean concentrations (bottom) (Source: EEA, 2017).

Concentrations of PM continue to exceed the EU limit values in large areas of Europe in 2015. PM10 concentrations above the EU daily limit value (50 μg/m^3) were registered at 19 % of the EU-28 reporting stations, especially in the urban regions of Italy, Poland, and Balkan Peninsula (Figure 1.3). In Portugal, both the daily limit value and the annual limit value were exceeded in Lisbon and almost exceeded in Porto. The WHO recommends that a special attention should be given to PM because no threshold has been identified below which no damage to health is observed (WHO, 2006).

Typically the NO_2 concentrations are higher close to urban main roads/streets decreasing in urban background areas. The lowest concentrations are found in rural areas. In Europe, 10.5% of all stations measuring NO_2 registered exceedances of the annual mean limit value (40 µg/m^3) in 2015. In Portugal three cities (Lisbon, Porto, and Braga) exceeded the annual limit value (Figure 1.3).

Ozone is produced by photochemical reactions during transport of precursors from large metropolitan areas. Highest concentrations are observed in southern Europe during summer, when high insolation and temperatures occur. In Portugal, O_3 concentrations are high in rural stations due to the impact of urban plumes (e.g. from Porto and Lisbon). Current main air quality problems in Porto and Lisbon metropolitan areas are related to PM and NO_2 (APA, 2017).

1.2 Health effects of air pollution

Up to 30 % of Europeans living in cities are exposed to air pollutant levels exceeding EU air quality standards, and around 95 % are exposed to levels of air pollutants deemed damaging to health accordingly to the WHO Air Quality Guidelines (EEA, 2017). Estimates of the health impacts attributable to exposure to air pollution indicate that PM2.5 concentrations in 2014 were responsible for about 399 000 premature deaths originating from long-term exposure in EU-28. The estimated impacts on the population of exposure to NO_2 and O_3 concentrations in 2014 were around 78 000 and 14 400 premature deaths per year, respectively (EEA, 2017).

The elderly and children are particularly vulnerable to the health impacts. According with the Eurostat, the statistical office of the European Union, the EU27 population is projected to continue to grow older, with the share of the population aged 65 years and over rising from 17% in 2010 to 30% in 2060 (Eurostat, 2011). This point out that if air pollution will not be reduced in the near future, the number of vulnerable people to air pollution will increase, implying consequently increasing health care costs.

During the last decades, numerous epidemiological and toxicological studies reported a wide range of adverse health effects associated with short-term (hours, days) and long-term (months, years) exposure to air pollution (mainly PM10 and PM2.5) (Brook *et al.*, 2010; Ito *et al.*, 2005; Pope & Dockery, 2006; Rückerl *et al.*, 2011). The overall results strongly suggest that these effects follow a mostly linear concentration-response function and are likely to occur at low levels (Crouse *et al.*, 2015). Recent outcomes from a chronic study indicate an association between mortality and PM2.5 at levels well below the current annual WHO air quality guideline level (10 µg/m^3) (Beelen *et al.*, 2014a). Further, the International Agency for Research on Cancer (IARC) classified PM from outdoor air pollution carcinogenic to humans (Group 1) (Loomis *et al.*, 2013).

Adverse health effects due to PM exposure are initiated after inhalation and penetration into the lungs and bloodstream, leading to effects in the respiratory, cardiovascular, immune, and neural systems (Breysse *et al.*, 2013). In reality we are exposed to a mixture of pollutants, but only few are actually measured or modelled. The WHO project “Review of EVIdence on Health Aspects of Air Pollution – REVIHAAP” concludes that PM, NOx, SO_2 and O_3 are considered responsible for the health effects seen in epidemiological studies (WHO, 2013b). More studies need to be done to better comprehend the short-term and long-term health implications of the whole mixture of pollutants (cocktail effect).

1.2.1 Health indicators

Simple health indicators such as mortality and morbidity or combined indicators such as attributable burden of disease measures, or monetary costs are used to estimate the impact of air pollutants on health. The selection of the indicator(s) depends on the stressor studied, availability of data, skills, computer resources, and purpose of the study (Costa *et al.*, 2014). Usually the choice is made to show the potential policy action or inaction impact.

Mortality is the most studied health endpoint in association with air pollution. Mortality reflects reduction in life expectancy, while morbidity is related to illness occurrence. One reason is the widespread availability of mortality data for large populations, and another reason is its easy interpretation. Studies are performed on all-natural cause and cause-specific mortality such as cardiovascular and pulmonary mortality (Abbey *et al.*, 1999; Beelen *et al.*, 2014b; Lelieveld *et al.*, 2015; Newman *et al.*, 2009). Other terms used for this indicator are premature deaths, avoidable deaths, attributable cases of death, additional mortality, and death postponed. In all of these metrics the health effect is expressed as number of deaths (APPRAISAL, 2013; Costa *et al.*, 2014).

A morbidity indicator estimates changes in new or existing diseases in a target population, ranging from minor effects to serious conditions that may require hospitalization. Some of the morbidity metrics outcomes include specific diseases such as asthma, chronic obstructive pulmonary disease (COPD), congestive heart failure, and ischemic heart disease, or consist of nonspecific indicators such as hospital admissions for all respiratory causes or all cardiovascular causes (Costa *et al.*, 2014). Incidence and prevalence are measures of disease commonly applied in morbidity issues. Incidence conveys information regarding the risk of developing the disease, whereas prevalence indicates how wide spread the disease is (Costa *et al.*, 2014; Raaschou-Nielsen *et al.*, 2013; Viegi *et al.*, 2006).

Other measures weight mortality and morbidity metrics according to duration, for instance, by counting the number of years with the disease (YLD) or the years of life lost due to premature mortality (YOLL). Other more elaborate measures such as quality-adjusted life years (QALY) or disease-adjusted life years (DALY) are also frequently used (APPRAISAL, 2013; Falagas *et al.*, 2007; Krewitt *et al.*, 2002).

1.2.2 Exposure-Response Functions

The basis of health impact quantification is the correlation between two variables: exposure and effect. Criteria for quantifying relationships are: (i) severity of the health response, (ii) assumed causality of the association, and (iii) number of people affected (Costa *et al.*, 2014).The general approach in Health Impact Assessment (HIA) is to use an exposure-response function (ERF) linking the concentration of pollutants to which the population is exposed with the number of health events occurring in that population. Applied to a pollutant concentration and a baseline health outcome, the ERF allows computing the change in the health outcome associated with an alteration in the concentration of pollutant.

Most ERF are derived from epidemiological or toxicological studies. ERF may be reported as a relative risk (RR) of a certain health response for a given change in exposure or as a slope from a linear regression model, the choice of ERF influences the outcome of the HIA process. Therefore, selecting published and up-to-date ERF is recommended. Some North American studies such as the Harvard Six Cities study (Dockery *et al.*, 1993) or the American Cancer Society (ACS) Study (Pope *et al.*, 2004) and European cohort studies (Cesaroni *et al.*, 2014; Raaschou-Nielsen *et al.*, 2013) are used to link long-term air pollution exposure and mortality and morbidity. The WHO also published in 2013 a set of recommendations for cost benefit analysis in support of the European Union’s air quality policy revision including reference ERF and associated background information for mortality and several morbidity effects associated with short and chronic exposure to PM, O_3 and NO_2 (WHO, 2013a).

1.3 Air quality Integrated Assessment

Exposure to air pollutants is mostly beyond the control of individuals and requires actions by public authorities at local, national and even European/International levels (Monks et al., 2009). In order to reduce air pollution effects, particularly in cities where the majority of the population lives, it is important to define effective planning strategies for air quality improvement. For this purpose, in the EU and in accordance to the Air Quality Directive (2008/50/EC), Air Quality Plans (AQP) establishing emission abatement measures have to be designed and implemented by the Member States of the EU in exceedance areas (“zones and agglomerations”). Zones and agglomerations are areas designated by MS for the purposes of monitoring and assessing air quality.

When preparing AQP and abatement measures, models need to be used for a comprehensive analysis of the impact of these measures on the air quality. The use of models is not stated explicitly in the Air Quality Directive for this management activity (just for assessment purposes, in combination with measurements), but it is not possible to properly do this analysis without the appropriate models. Models are also useful to assess the causes of exceedances of air quality thresholds, and to provide information related with the contribution of the different emissions sources for the air quality (Denby *et al.*, 2010).

It is possible to mention three major reasons to use numerical models, even though numerical tools are often seen as more inaccurate that measuring tools: i) better spatial coverage; ii) modelling can be applied prognostically, for instance to predict the future air quality as result of air quality mitigation measures; and iii) modelling allows an understanding of the sources, causes and processes (physical and chemical transformations) that influence the air quality (EEA, 2011).

In the last two decades atmospheric modelling has experienced important improvements. Nowadays, a large variety of modelling systems and options exist, from complex to more simpler ones (such as TAPM (Hurley, 2008) and CHIMERRE (Schmidt *et al.*, 2001)), covering from regional to urban scales, or even street level scales (such as VADIS (Borrego *et al.*, 2003; Rodrigues *et al.*, 2018)). In particular chemical transport models have become widely used tools for assessing the effectiveness of control strategies adopted by regulatory agencies. A comprehensive listing of air quality models used in Europe can be found in the European Environment Information and Observation Network (EIONET) Model Documentation System (MDS) (URL2). In general, the following model types can be distinguished: Gaussian and non-Gaussian parameterized models, Statistical models, Computational Fluid Dynamics models (CFD), Lagrangian particle models, Lagrangian chemical models and Eulerian chemical transport models.

State-of-the-art models include online Chemical Transport Models, which allow the study of feedback interactions between meteorological and chemical processes within the atmosphere. Examples of such models are the WRF-CHEM (Grell *et al.*, 2005) or the European COSMO-ART (Vogel *et al.*, 2009) models. An important trend is the inclusion of atmospheric chemistry modules in earth system models, in which the links between climate, atmospheric composition and the biosphere can be studied (APPRAISAL, 2014).

Notwithstanding the wide range of different modeling tools that have been developed and applied by EU MS in the last decades to assess the effects of local and regional emission abatement policy options on air quality, this kind of tools do not include exposure estimations or indicators related to health. To solve this gap the air quality modeling community created in the last years a research stream called Integrated Assessment Modelling (IAM), aiming to better support the society and in particular the policy and decision-making processes (Amann *et al.*, 2011; Oxley *et al.*, 2013). IAM can be used to assess the effects on air quality and consequentially health or environmental impacts of an emission abatement policy. If several emission abatement policies are considered the IAM can help the user to decide which set of measures should be selected based on some criteria (e.g. minimization of cost, health impact or the most socially acceptable option). While most practical IAM applications rely on expert judgement in this decision process, some IAM systems can assist the user to determine the “best” set of abatement measures through an optimization process (Miranda *et al.*, 2014).

Based on the Drivers – Pressures – State – Impacts - Responses (DPSIR) scheme, originally proposed by the EEA (EEA, 1999) “to structure thinking about the interplay between the environment and socioeconomic activities”, it is possible to define two alternative IAM approaches to improve air quality: (a) the scenario analysis, which consists in defining a set of abatement measures and assessing its impact on air quality through modeling (occasionally health impacts are also estimated), (b) the optimization analysis which uses algorithms to automatically minimize costs and/or maximize benefits on top of the emission-concentration relationships with a view of delivering a set of cost-efficient abatement measures to the policy-maker. Figure 1.4 displays the two alternative approaches.

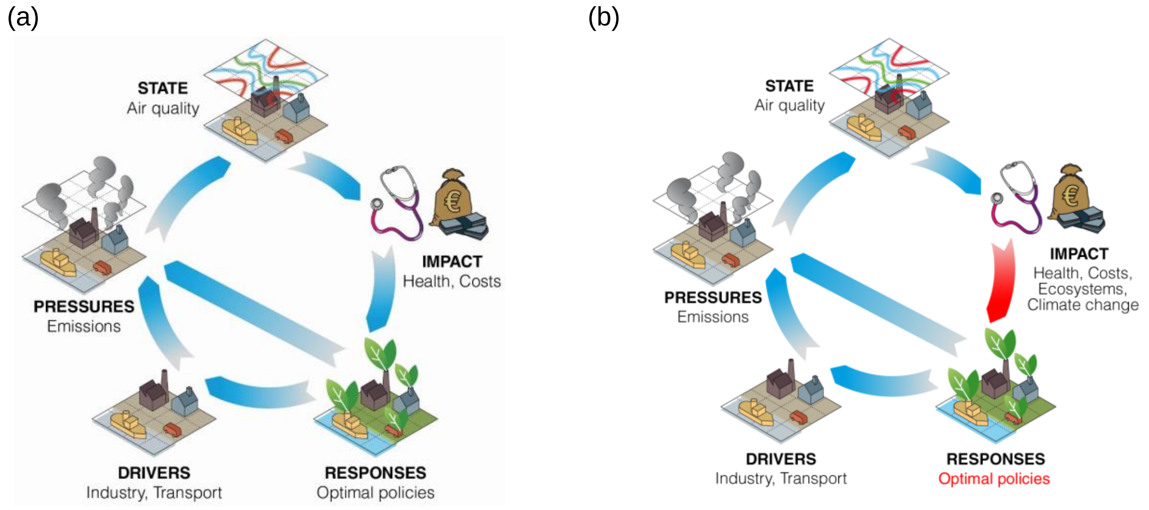


Figure 1.4 - Integrated assessment modelling approaches following the DPSIR scheme: (a) scenario analysis; (b) optimization approach (Source: URL3).

A list of technological abatement measures, including costs and emissions effects, is available on the GAINS database (URL4), and can be used in IAM. While measures (issued from local expert’s knowledge and judgment) are the input in the scenario analysis, they constitute the final results of the optimization (Thunis *et al.*, 2016a). An overall review of the methodologies that are used in different MS in the scope of local and regional AQP has been performed during the APPRAISAL EU FP7 project (URL3). It was possible to conclude that in the phase of design and assessment of AQP, IAM is currently mainly performed through scenario analysis, while more elaborated methods using optimization methods still remain in the research projects. Regarding the main IAM component, i.e. air quality modeling, there are many different models reported to be applied but none is a standard or preferred modelling tool (Thunis *et al.*, 2016a).

The Partnership on Air Quality (EU, 2017), one of the 12 priority themes of the “Urban Agenda for the EU”, delivered a report in 2017 emphasizing the importance of knowledge on the impact/effectiveness of air quality measures (not only regarding contributions to emission reduction, but especially on health effects improvement and related external cost gain), and stating that there is a “lack of access to modelling approaches to assess the impact of measures, and difficulties in implementing and use them”. It also mentions that communication to the general public should be improved and would focus more on measurable benefits generated in terms of well-being or quality of life improved.

1.4 Objectives and outline of the thesis

The principal objective of this thesis is to explore the capabilities of Integrated Assessment Modelling tools to cost-efficiently evaluate measures to improve the air quality, in particular in urban areas.

This main goal depends on some specific objectives, namely:

i. to review current integrated assessment methodologies, from simple (e.g. scenario approach) to more comprehensive ones (e.g. optimization approach), used to improve air quality, aiming to better understand current strengths and weaknesses.
ii. to design and build a new simple integrated urban air pollution assessment system able to select effective air pollution abatement strategies taking into consideration human exposure levels.
iii. to evaluate the developed system through its application to a selected urban case study.
iv. to explore the system with different case study scenarios/measures to improve the air quality.

Two main outcomes of these objectives will be: (a) a critical review on integrated assessment methodologies in the scope of plans to improve urban air quality; and (b) an integrated assessment system specifically adapted and tested to urban scale applications.

The system aims to be innovative by including social aspects, health effects, and costs in the decision process. Moreover, it should be focused on the urban scale were air pollution is more relevant, and should be able to quickly process and analyze different options, by incorporating state-of-the-art techniques. To achieve the thesis main objectives the structure shown in Figure 1.5 was designed and adopted.

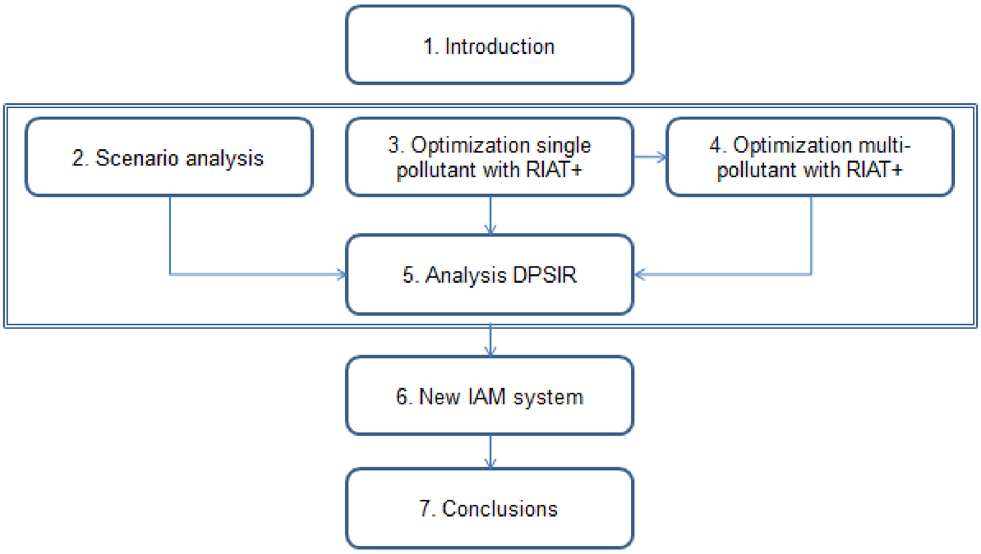


Figure 1.5 - Overview of the thesis structure.

Chapter 1 has provided an overview of the scientific context of this thesis. Emission trends in Europe and Portugal and their main sources, current air quality levels, and the legal framework have been introduced. The main focus was placed on urban areas, where the emission sources as well as exposed population are concentrated. Moreover, this Chapter includes a state-of-the-art in health effects of air pollution and of air quality modelling for air quality management purposes. Taking into consideration all this information, the objectives to be achieved within this Ph.D. thesis have been stated.

Chapter 2 explores the scenario approach to identify the impact of different emission abatement measures. It assesses based on a scenario analysis the potential air quality improvements resulting from the implementation of four emission reduction scenarios, in a particular urban area: the replacement of 10% of vehicles below EURO 3 standards by hybrid models; the introduction of a Low Emission Zone (LEZ); the replacement of 50% of the fireplaces; and the application of clean technologies to industry.

Chapter 3 focus on Integrated Assessment Models (IAM) to determine suitable abatement measures to improve the air quality. In this sense, the Regional Integrated Assessment Tool (RIAT+) was tested for two European cases: the Brussels Capital Region (Belgium) and the Porto Urban Area (Portugal), in scenario analysis and optimization mode, respectively.

Chapter 4 tests the RIAT+ system in optimization mode for a multi-pollutant case (PM10 and NO_2) and an additional set of improvement measures.

Chapter 5 adapts the general DPSIR scheme to Integrated Assessment Modeling and compares the scenario and the optimization approaches.

Based on knowledge from the work developed and described in the framework of the previous chapters, which allowed identifying advantages and limitations of IAM tools and approaches, an urban integrated assessment modelling system to support decision-making was formulated and tested. **Chapter 6** describes this application over Porto Urban Area.

Chapter 7 summarizes the main harmonized conclusions of this thesis, and provides recommendations for future research.

This thesis comprises adapted versions of published or submitted papers to peer-reviewed Science Citation Index (SCI) journals. The papers alterations concern both references and document formatting, in order to make the text easier to read. In most papers, the author was responsible for the study design, as well as for the results analysis and for the manuscript writing. The co-authors were responsible for the critical revision of the manuscript, and, when applicable, to perform modeling simulations and provide software support (e.g. Chapter 3). Part of the work was done during my stay at the University of Brescia, Italy.

2 Evaluating Strategies to Reduce Urban Air Pollution

Abstract

During the last years, specific air quality problems have been detected in the urban area of Porto (Portugal). Both PM10 and NO_2 limit values have been surpassed in several air quality monitoring stations and, following the European legislation requirements, Air Quality Plans were designed and implemented to reduce those levels. In this sense, measures to decrease PM10 and NO_2 emissions have been selected, these mainly related to the traffic sector, but also regarding the industrial and residential combustion sectors. This study aims to investigate the efficiency of these reduction measures with regard to the improvement of PM10 and NO_2 concentration levels over the Porto urban region using a numerical modelling tool – The Air Pollution Model (TAPM). TAPM was applied over the study region, for a simulation domain of 80×80 km^2 with a spatial resolution of 1×1 km^2. The entire year of 2012 was simulated and set as the base year for the analysis of the impacts of the selected measures. Taking into account the main activity sectors, four main scenarios have been defined and simulated, with focus on: (1) hybrid cars; (2) a Low Emission Zone (LEZ); (3) fireplaces; and (4) industry. The modelling results indicate that measures to reduce PM10 should be focused on residential combustion (fireplaces) and industrial activity and for NO_2 the strategy should be based on the traffic sector. The implementation of all the defined scenarios will allow a total maximum reduction of 4.5% on the levels of both pollutants.

This chapter was published as:

Duque, I., **Relvas, H.**, Silveira, C., Ferreira, J., Monteiro, A., Gama, C., Rafael, S., Freitas, S., Borrego, C., Miranda, A. I. (2016). Evaluating strategies to reduce urban air pollution. *Atmospheric Environment,* 127**,** 196-204.

I mainly contributed to TAPM scenarios creation, modelling simulations, and results analysis, and I also contributed to the writing and revision of this paper.

2.1 Introduction

Air quality is one of the environmental areas in which the European Union (EU) has been most active, in particular designing and implementing legislation on air quality and on the restriction of pollutant emissions to the atmosphere. The Directive on Ambient Air Quality and Cleaner Air for Europe (Directive 2008/50/EC), published in May 2008, highlights modelling as a fundamental tool to improve air quality assessments and management. The Directive also reinforces the obligation of EU member states to elaborate and implement Air Quality Plans (AQP) to improve air quality when standards are not fulfilled. The implementation of AQP, when pollutant concentrations exceed the air quality standards in zones or agglomerations, should be based on the development of measures that reduce the pollutant atmospheric concentrations and meet the legal requirements (Miranda *et al.*, 2014; Miranda *et al.*, 2015).

Exceedances of the thresholds of particulate matter (PM10) and nitrogen dioxide (NO_2) have been reported in the urban agglomeration of Porto Litoral, where human exposure is also high (Borrego *et al.*, 2009; Miranda *et al.*, 2014). Air Quality Plans were developed for both pollutants: during the period 2005-2008 for PM10 and in 2010 for NO_2 (Borrego *et al.*, 2012a; Borrego *et al.*, 2012b). Despite improvements in air quality, verified after the 2008-2010 period, there is still a requirement for the reduction of the concentrations of these pollutants, because some of the legislated limits continue to be exceeded every year in particular monitoring sites.

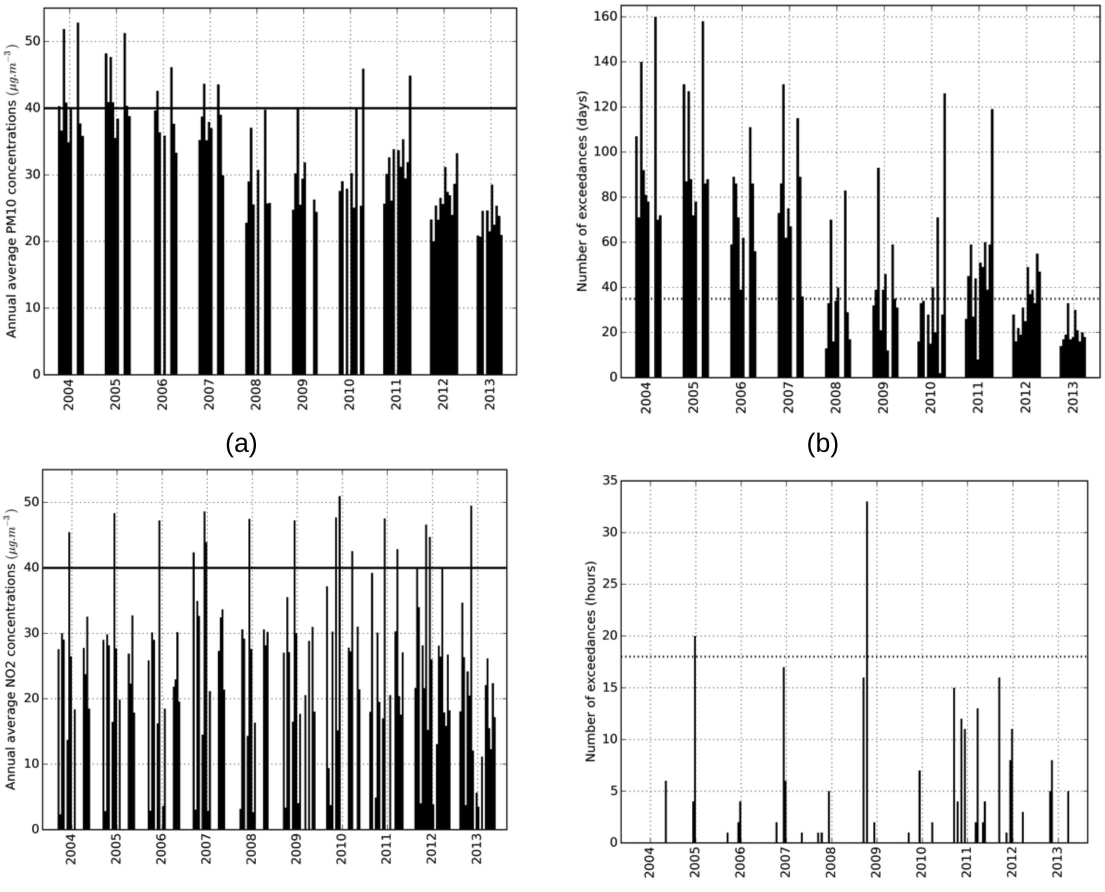
Due to their ability in assessing the efficiency of different emission reduction measures, air quality numerical models are useful tools for air quality management. They estimate pollutant concentrations in areas that are not covered by air quality monitoring stations and quantify the impact of projected emission scenarios on air quality. Air quality models have been used by several EU Member States in the scope of designing AQP for European zones/agglomerations (Nagl *et al.*, 2007). Eulerian Chemical Transport Models (CTM) are the most frequently used (APPRAISAL, 2014) requiring the emissions estimated for several activity sectors, meteorological variables and initial and boundary conditions as input data. The Air Pollution Model (TAPM) (Hurley *et al.*, 2005) is particularly suited to evaluate the impact of emission reduction strategies due to its flexibility, user friendly environment and short time demands in terms of computational efforts for long term simulations (1 year) compared to other CTM models. TAPM has been previously applied and validated over several Portuguese areas (Borrego *et al.*, 2012b; Ribeiro *et al.*, 2007).

The main objective of this study is to investigate the most efficient measures to reduce PM10 and NO_2 concentration levels, quantifying this reduction and supporting future additional AQP and policy-makers for the air quality management over urban areas, such as the Porto Litoral agglomeration.

The present chapter is organized as follows: Section 2.2 presents the PM10 and NO_2 concentrations registered over the last decade, followed by description of the air quality modelling system and its setup/application over the Porto urban region in Section 2.3. The measures (emission reduction scenarios) to reduce PM10 and NO_2 concentrations are proposed in Section 2.4, their efficiency/impact is analyzed and discussed in Section 2.5. Finally, the summary and conclusions are drawn in Section 2.6.

2.2 PM10 and NO_2 measured in the Porto urban region

Figure 2.1 presents the evolution of the annual mean concentrations of PM10 and NO_2, together with the number of days in exceedance regarding the daily legal limits, registered between 2004 and 2013 in the monitoring sites located in the Porto metropolitan area.



(a) (b)

(c) (d)

Figure 2.1 - (a) PM10 annual average concentrations and the respective limit value (black line; 40 µg.m^{-3}); (b) number of exceedances of the daily limit value of PM10 (50 µg.m^{-3}) (dotted line: number of allowed exceedances – 35); (c) NO_2 annual average concentrations and the respective limit value (black line; 40 µg.m^{-3}); (d) number of exceedances of the hourly limit value of NO_2 (200 µg.m^{-3}) (dotted line: number of allowed exceedances – 18), registered at the air quality stations of the Porto metropolitan area during 2004-2013.

Regarding PM10, the exceedances to the annual and daily limit values (Figure 2.1, (a) and (b)) decreased considerably after the implementation of the 2008 AQP for PM10. For NO_2, the air quality improvement after this AQP is less notorious (Figure 2.1, (c) and (d)). Besides the AQP strategy, the financial crisis also contributed to the reduction of pollutant emissions and consequently to the air quality improvement (Ribeiro *et al.*, 2014). The average daily profiles of PM10 and NO_2, displayed in Figure 2.2 enable the understanding and characterization of the major causes of measured levels at the different monitoring sites.

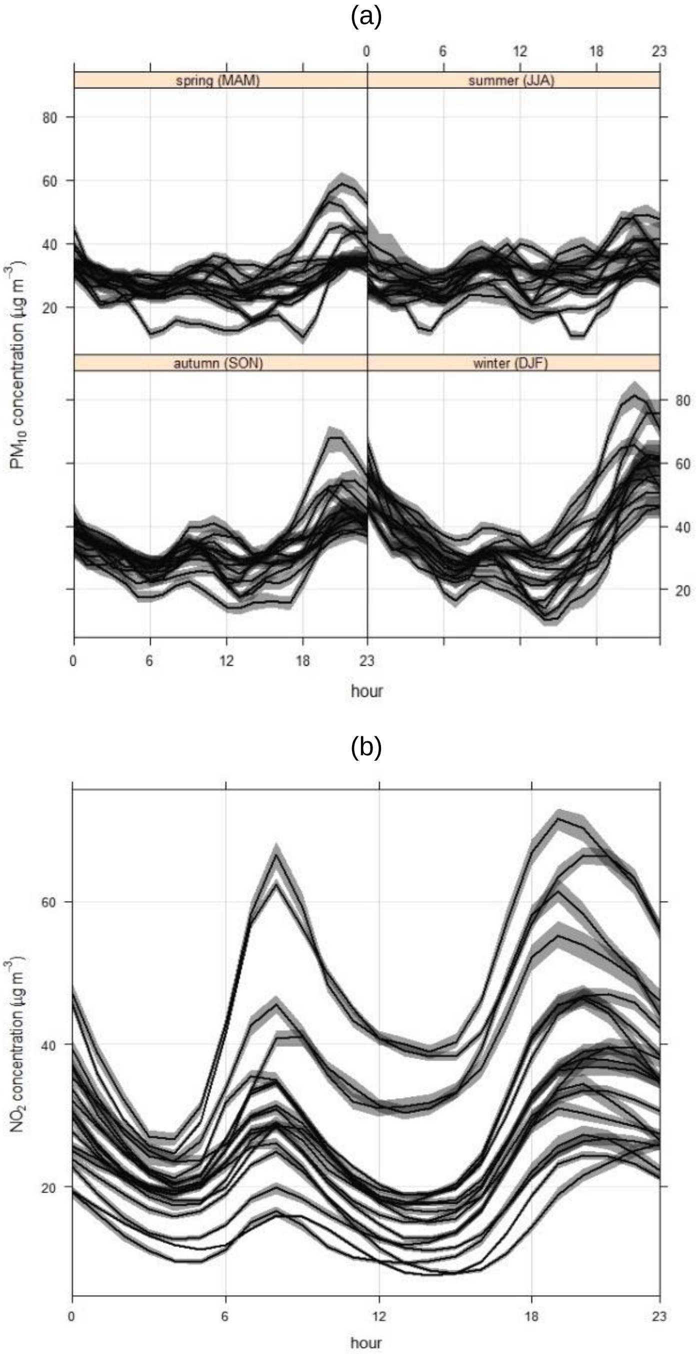


Figure 2.2 - Averaged daily profiles of (a) PM10 (grouped by season), and (b) NO_2 concentrations, measured in Porto Urban Area during the 2004-2013 period.

The PM10 daily profiles, grouped by season, show that the highest concentrations are observed at night, reaching maximum values during the winter period, which can be related to residential combustion activities. Regarding NO_2, the daily profiles (similar behavior among the seasons) follow the traffic diurnal cycle, with peaks in the morning and late afternoon. This characterization supported the establishment of more appropriate emission reduction scenarios to mitigate concentrations of these pollutants.

In order to evaluate the impact of the proposed measures on the improvement of atmospheric PM10 and NO_2 levels, the air quality modelling system TAPM (section 2.3) was applied to the current situation (base scenario) and to several emission reduction scenarios (section 2.4).

2.3 Air quality modelling system

The model selected to perform the air quality simulation over the study region was “The Air Pollution Model” (TAPM) (Hurley et al., 2005), developed by the Australia’s Commonwealth Scientific and Industrial Research Organization (CSIRO). This model is a 3-D Eulerian model, made of two modules which calculate meteorological conditions and air pollution concentrations based on fundamental fluid dynamics and scalar transport equations. Technical details of the model equations, physical and chemical parameterizations, as well as its numerical methods, are described by Hurley *et al.* (2005).

In the TAPM meteorological module, global databases of terrain and land use from the Earth Resources Observation Systems (EROS), surface temperature from the US National Centre for Atmospheric Research (NCAR), and synoptic conditions from the Limited Area Prediction System (LAPS) and Global Analysis and Prediction (GASP) models from the Bureau of Meteorology (BOM) were used. This module solves the momentum equations for horizontal wind components, the incompressible continuity equation for the vertical velocity in a terrain-following coordinate system, and scalar equations for potential virtual temperature, specific humidity of water vapour, cloud water and rain water. This first module provides the meteorological forcing necessary for the air quality simulation.

The air pollution module of TAPM consists of an Eulerian grid-based set of prognostic equations for pollutant concentration, with optional pollutant cross-correlation equations to represent counter-gradient fluxes, and an optional Lagrangian particle mode for near-source concentrations. The Eulerian grid module was applied and consists of nested grid-based solutions of the Eulerian mean concentration and optional variance equations representing advection, diffusion, chemical reactions and emissions. Dry and wet deposition processes are also included. Besides the meteorological outputs, the air pollution module considers the air pollutant emissions from several sources, such as: point sources, line sources, gridded surface emissions, biogenic surface emissions, among others. Regarding the simulation of the point sources, plume buoyancy, momentum and building wake effects are considered. 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 *et al.*, 2005).

TAPM was applied over the study region using synoptic data provided by CSIRO. The application considered three domains using a nesting approach: the outer domain includes part of the Iberian Peninsula (D1), D2 covers Northern and Central Regions of Portugal, and the inner domain contains the Porto urban area (D3), with a resolution of 10, 3 and 1 km^2, respectively. The air pollution module, using chemistry mode, was applied for the inner domain (D3) with an area of 80×80 km^2 (see Figure 2.3).

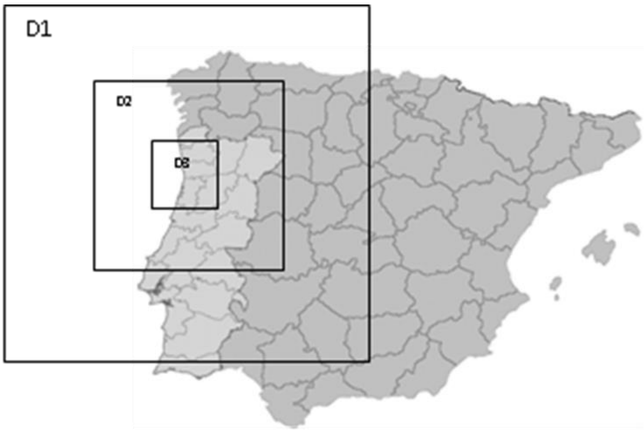


Figure 2.3 - The simulation domains used in the TAPM modelling application

TAPM was applied for the year 2012, corresponding to the most updated national emission inventory report (APA, 2014).The annual emissions information is disaggregated by municipality and divided by SNAP (Selected Nomenclature for Air Pollution) categories: commercial and residential combustion (SNAP 2); industrial combustion (SNAP 3); production processes (SNAP 4); extraction and distribution of fossil fuels and geothermal energy (SNAP 5); solvent and other product use (SNAP 6); road transport (SNAP 7); other mobile sources and machinery (SNAP 8); waste treatment and disposal (SNAP 9). The annual emission data for each pollutant and activity sector was spatially and temporally disaggregated using a top-down approach in order to obtain the required resolution for the selected simulation domain (Monteiro *et al.*, 2007). SNAP 1 (energy production) emission sources and the larger sources of SNAP 3 and 4 were considered as point sources, summing a total of 8 within the modelling domain. As for transport emissions (SNAP 7), a fraction of the emissions were considered as line sources, for the urban area of Porto and for the motorways in the domain. Line source emissions were estimated using the TREM model (Transport Emission Model for Line Sources) (Borrego *et al.*, 2004) based on available traffic counts and on statistical data of the fleet composition. The background concentrations, required by the model, were obtained through estimates of the average values of the background air quality stations of the study area for 2012.

This modelling system has already been extensively applied over Portugal and the Porto region, exhibiting good agreement when compared/validated against observational data (Borrego *et al.*, 2012a; Miranda *et al.*, 2014).

2.4 Emission reduction scenarios

Additional measures, required to reduce the PM10 and NO_2 concentrations and decrease the exceedances to the legislated limits, were investigated and selected for further assessment.

The criteria used for the selection included: (i) relative contributions of each activity sector to the total pollutant emissions; (ii) types of exceedances (annual/daily) and the monitoring sites where they were registered; (iii) actions already included in the defined and implemented AQP.

Following these criteria, and with the prior knowledge that the main contributing sectors are residential combustion, industry and traffic, and that the monitoring sites with higher concentrations are located in urban and traffic sites, a group of 4 main scenarios were defined:

- Scenario 1: Replacement of 10% of vehicles below the EURO3 class (diesel and gasoline) by hybrid model vehicles;
- Scenario 2: Introduction of a Low Emission Zone (LEZ) on a specific polluted area of Porto city, with the restriction for vehicles below EURO3;
- Scenario 3: Replacement/reconversion of 50% of the conventional fireplaces by more efficient equipment (residential combustion);
- Scenario 4: Application of clean technologies that allow a reduction of 10% in PM10 emissions from production processes and industrial combustion.

2.4.1 Scenario 1: Replacing vehicles below EURO 3 by hybrid cars

The European emission standards (EURO) define, since 1992 (with EURO 1) the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards are defined in a series of EU directives representing the progressive introduction of increasingly stringent standards. At the moment, EURO 5 and EURO 6 already entered into force (September 2009 and January 2014, respectively) aiming to reduce the emissions of PM (EURO 5) and NOx (EURO 6) from diesel cars (Lopes *et al.*, 2014). In this context, this scenario considers the replacement of 10% of the oldest vehicles (previous to EURO standards, EURO 1 and EURO 2) by more environmental friendly models, namely hybrid cars, which are powered by both an internal combustion engine and an electric motor, and emit, on average, less pollutants quantities than the conventional diesel/petrol cars (Soret *et al.*, 2014). For the study region, this replacement corresponds to a total of 30 800 vehicles.

Traffic emissions were estimated using the TREM (Transport Emission Model for Line Sources) model (Borrego *et al.*, 2004). This emissions model was already comprehensively applied and tested for urban areas of Portugal (Borrego *et al.*, 2006).

2.4.2 Scenario 2: Low Emission Zone (LEZ)

A Low-Emission Zone (LEZ) is a confined area where access by certain vehicles is restricted or prohibited with the aim of improving the air quality. The LEZ defined in this study (Figure 2.4) includes an area with high traffic density, where one of the air quality monitoring sites with NO_2 and PM10 exceedances is located.

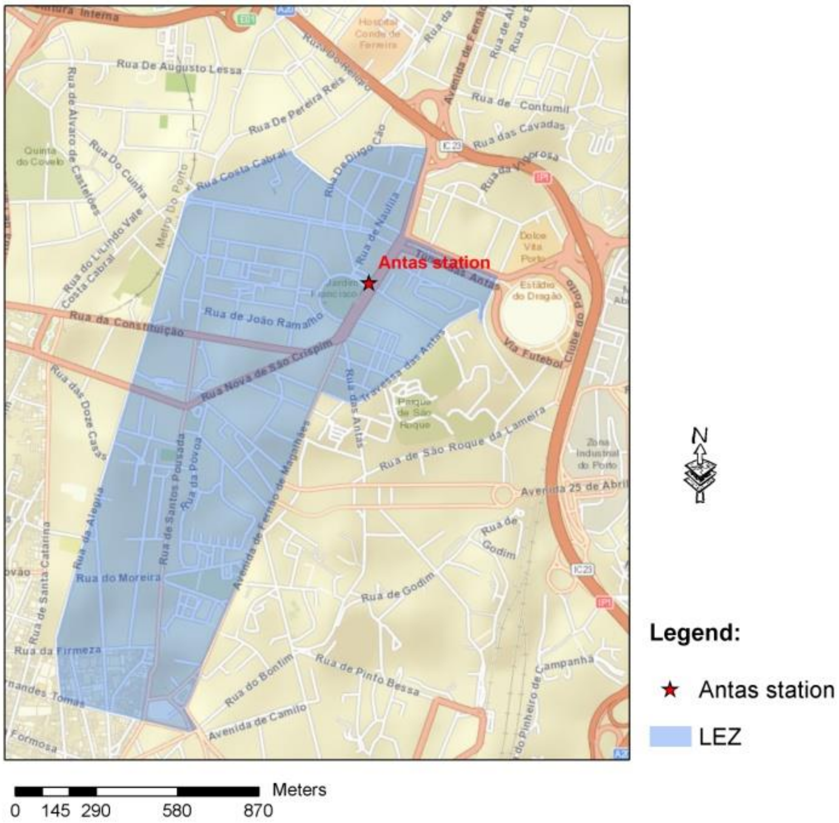


Figure 2.4 - The selected Low Emission Zone (LEZ).

Figure 2.4 displays the extension of the area (approximately 1.5 km^2), the main streets and avenue together with the location of the monitoring station (Antas). It was assumed that vehicles above and including EURO 3 were allowed to pass through this restricted area.

2.4.3 Scenario 3: Fireplace reconversion

Residential combustion is a major contributor to the total PM10 emissions, as reported by the Portuguese emission inventory (APA, 2014; Borrego *et al.*, 2010) and also worldwide (Hedberg *et al.*, 2002; Johansson *et al.*, 2004; Jordan & Seen, 2005; McDonald *et al.*, 2000). Johansson et al. (2004) showed that PM emissions are considerably higher from a wood stove or a fireplace, i.e., from uncontrolled combustion devices, than from controlled devices. One of the most important variables, that influences wood combustion emissions, is the air flow supply (Jordan & Seen, 2005). According to studies conducted by the United States Environmental Protection Agency (URL5), replacing traditional fireplaces with certified wood burning appliances can result in a reduction of over 80% in PM emissions. In this context, this scenario considers the replacement of 50% of the traditional fireplaces by more efficient equipment (such as heat recovery systems).

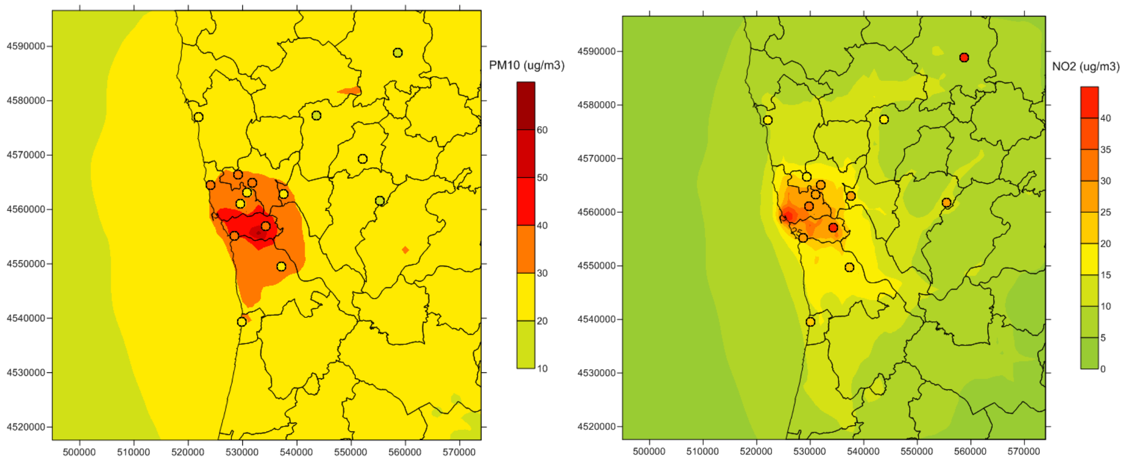
The emission reduction associated to this measure was calculated on the basis of: fuel (wood) consumption per district (Gonçalves *et al.*, 2012), type of residential combustion equipment per sub-municipality (INE, 2012a) and emission factors used by APA (2014). Considering that the reconversion/replacement of the conventional fireplaces allows a reduction of 70% (URL4) of PM10 emissions, a maximum reduction (per grid cell of the simulation domain) of 35% of the total emissions from residential combustion was estimated.

2.4.4 Scenario 4: Industrial clean technologies

Industrial combustion (SNAP 3) and production processes (SNAP 4) are also important sources of total PM10 emissions, as reported by the Portuguese emission inventory (APA, 2014). The emission reduction associated to this measure was calculated under the assumption that it is possible to reduce 10% of PM10 emissions using new clean technologies on both macrosectors. These clean technologies include high efficiency de-dusters (cyclones, electrostatic precipitators and good practice in industrial processes- storage and handling, leak detection and repair program). The removal efficiencies associated to these technologies can be found in the GAINS database (technology database), which contains a large dataset collected for Portugal by the International Institute for Applied Systems Analysis (IIASA) (URL6).

2.5 Analysis of results

The TAPM model was applied for the base scenario and for each reduction scenario. Figure 2.5 displays the results obtained with the TAPM application for the base scenario (year 2012) regarding the annual average of PM10 and NO_2. The measured annual averages (URL7) are also represented (by small circles) using the same colour scale.

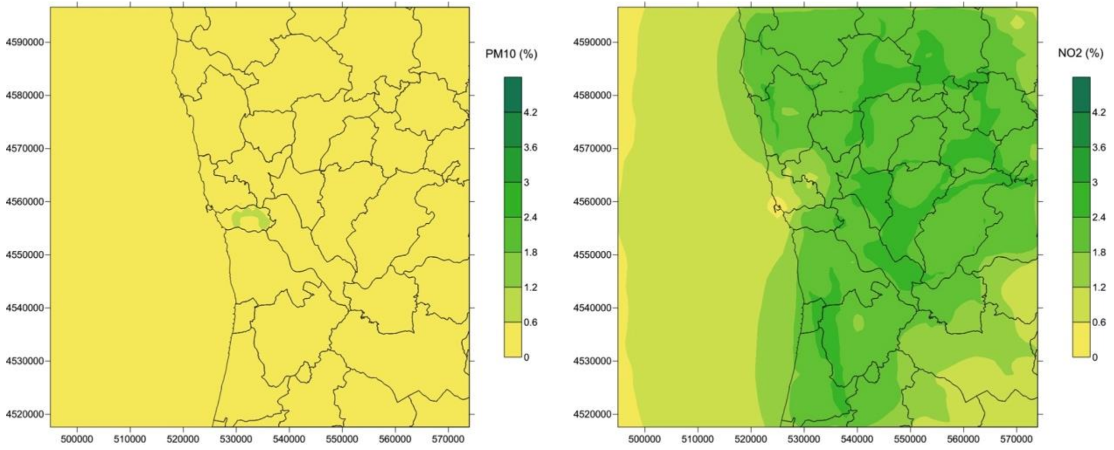


(a) PM10 (b) NO_2

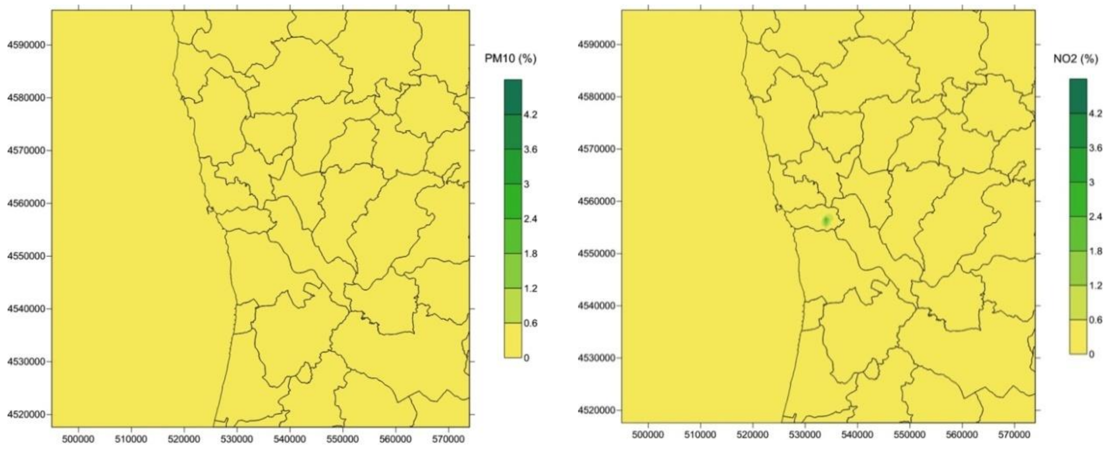
Figure 2.5 - Annual average concentrations of PM10 (a) and NO_2 (b) simulated with TAPM for the base scenario (year 2012). The small circles indicate the annual average values measured at the monitoring sites. The coordinates (scale) are UTM (meters).

The modelling results show higher annual averages of both pollutants ([PM10]>30 $\mu g.m^{-3}$ and [NO_2]>25 $\mu g.m^{-3}$) mainly over the Porto municipality and the surrounding area, where concentrations higher than the legislated limit values are expected. The rest of the domain is characterized by low annual concentrations ([PM10]≅15-20 $\mu g.m^{-3}$ and [NO_2]≤10 $\mu g.m^{-3}$). The comparison with observed values indicates that TAPM over-predicts PM10 concentrations in the urban area and under-predicts NO_2. Figure 2.6 presents the expected reductions (in terms of percentage) obtained with each scenario for both pollutants (PM10 and NO_2).

PM10 **Scenario 1. Hybrids** NO_2



Scenario 2. LEZ



Scenario 3. Fireplaces

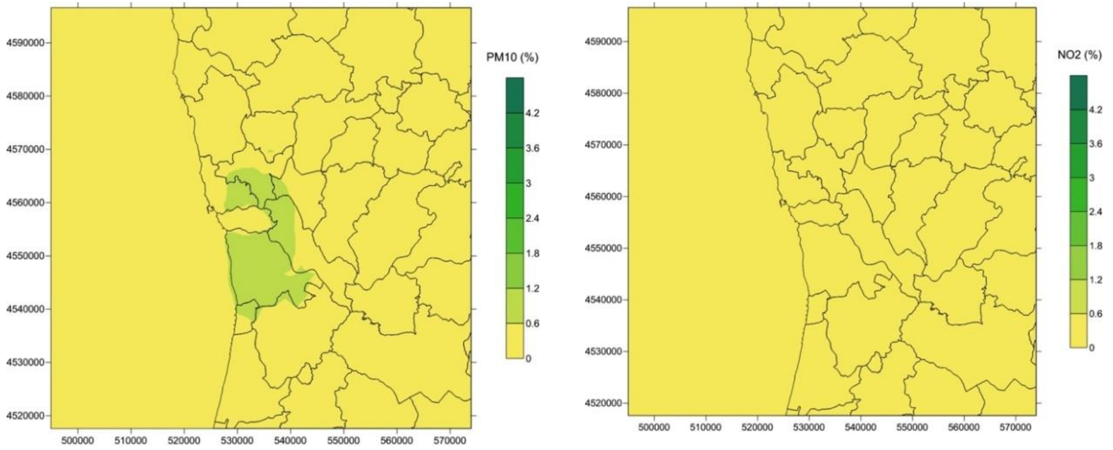


Figure 2.6 - Modelling results: (left) percentage reduction of PM10 and (right) NO_2 concentrations, comparing each scenario to the base case. The coordinates (scale) are UTM (meters).

PM10 **Scenario 4. Industry** NO_2

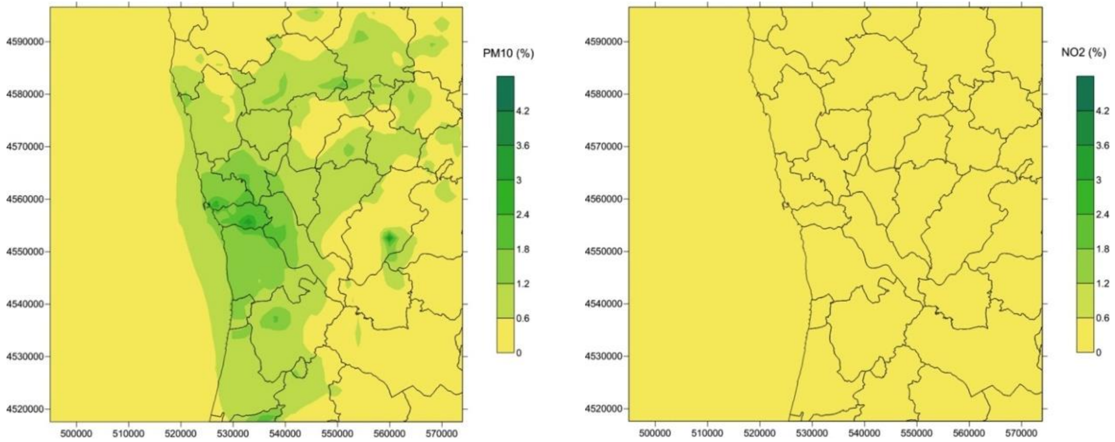


Figure 2.6 – (Continued, legend on page 25).

The modelling results show that the traffic measures (Scenarios 1 and 2) are the only ones that have impact on NO_2. Scenario 1 (hybrid cars) results in a reduction of NO_2 levels of up to 4.5% over all the domain, while the LEZ implementation (Scenario 2) only has a local benefit with a local reduction of the annual concentration of NO_2 reaching 3%. The other two scenarios (3 and 4) only result in reductions of PM10 concentrations. The reconversion of fireplaces (Scenario 3) allows reductions of up to 1.5% on the annual average of PM10 in a zone around the municipality of Porto (where a higher density of equipment is located). Higher reductions are expected with the application of measures to the industrial sector (Scenario 4), in terms of magnitude (up to 3.5%) and spatial coverage.

Figure 2.7 displays the simulated reduction when applying all the selected measures simultaneously (all scenarios included) in order to assess the maximum mitigation achieved with the identified measures.

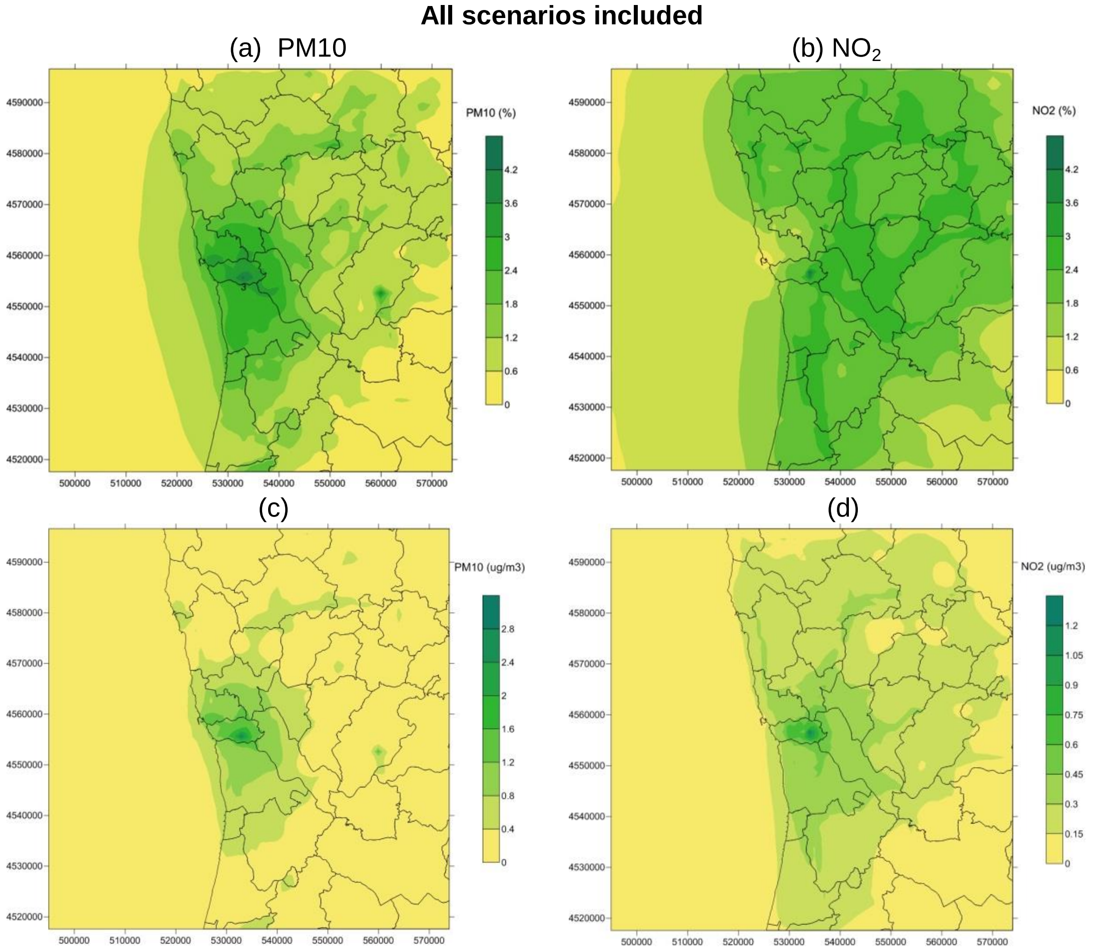


Figure 2.7 - Reduction in percentage (a,b) and absolute concentration (c,d) in annual concentrations considering all mitigation measures combined for PM10 and NO$_2$ (when compared to the base case).The coordinates (scale) are UTM (meters).

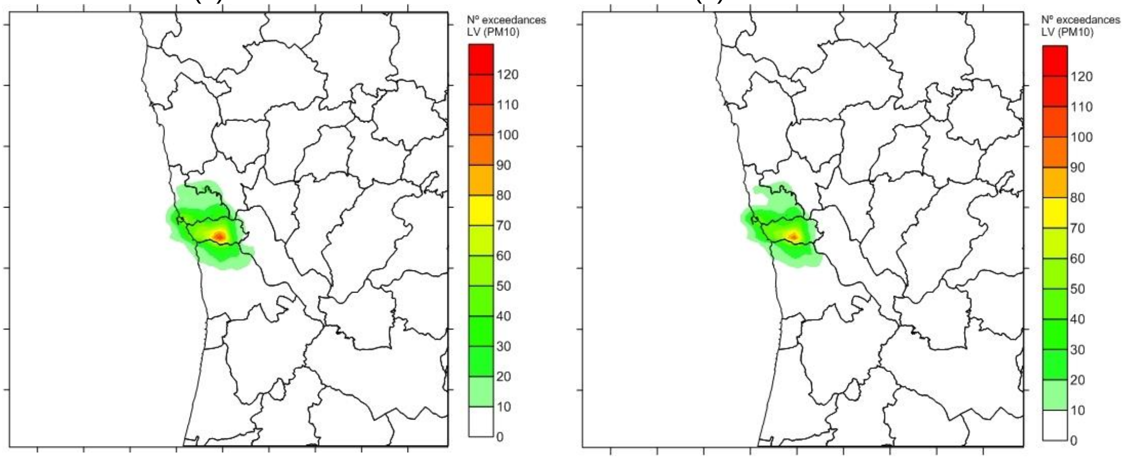
The combination of all the referred measures allows a total reduction of 4.5% for both pollutants, mainly over the area of Porto for PM10 and extended across the overall domain regarding NO$_2$. This corresponds to reductions of up to 2.8 µg.m^{-3} for PM10 and up to 1.2 µg.m^{-3} for NO$_2$.

In order to check the success of these mitigation measures, the fulfilment of the legislated limit values was analysed for both pollutants, regarding the daily and hourly limit values (LV) for human health protection for PM10 and NO$_2$, respectively. Figure 2.8 presents the results expected in terms of exceedances to the LV comparing both cases (base case and considering all mitigation measures).

PM10

(a) Base case

(b) All scenarios included



NO_2

(c) Base case

(d) All scenarios included

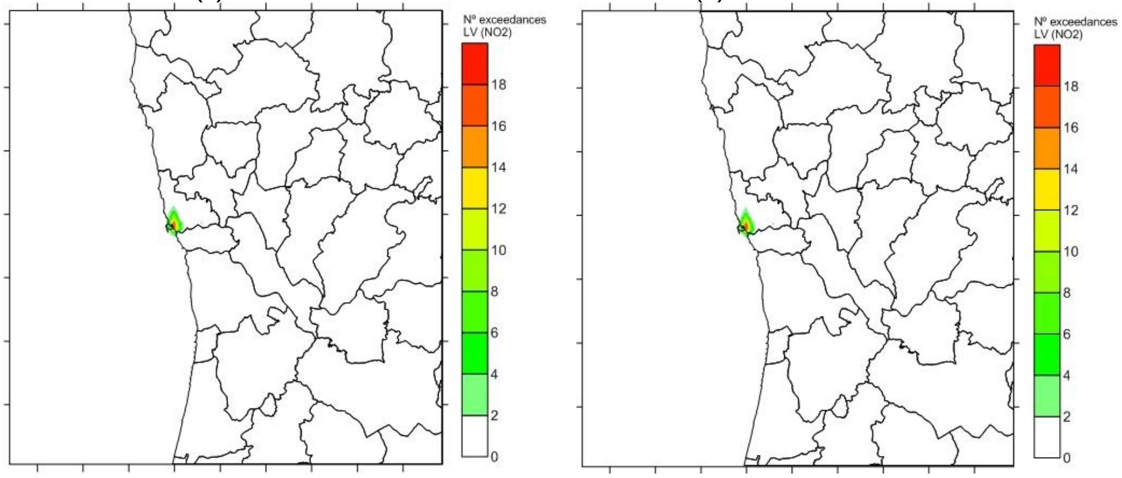


Figure 2.8 - Number of exceedances to the daily limit value of PM10 and to the hourly limit value of NO_2 expected for base case (a, c) and all scenarios included (b, d).

In the case of PM10, besides the prevalence of the non-fulfilment condition in both cases, there is a substantial reduction on the number of exceedances to the daily LV foreseen with the mitigation measures scenario (around 30% of reduction). Regarding NO_2, the fulfilment of the legislation already exist in the base case (a maximum of 18 hours with exceedances are allowed) and continues in the scenario case (with a reduction of 10% of the maximum values).

These modelling results, together with the corresponding methodology, will be particular important to policy-makers in taking future decisions and to define strategy for near future in order to improve and solve current situations of non-compliance of air quality legislation.

2.6 Conclusions

This study aims to investigate additional mitigation measures to be applied in order to solve the exceedances in concentrations of PM10 and NO_2 registered over the metropolitan area of Porto, verified after the development and implementation of Air Quality Plans. Considering the main contributing emission sectors for these pollutants, four main scenarios were defined: (1) replacement of 10% of vehicles below EURO 3 by hybrid models; (2) introduction of a Low Emission Zone (LEZ); (3) reconversion of 50% of the fireplaces; and (4) application of clean technologies to industry. These emission scenarios, together with the base scenario (year 2012), were simulated with the TAPM modelling system (already validated for the Porto region in previous studies) in order to assess their impacts on air quality. The results indicate that none of the identified measures produces important reductions for both pollutants simultaneously. In the case of PM10, the strategy should focus on industrial activity and residential combustion. Regarding NO_2, measures should be related to the traffic sector. A LEZ is suggested only for specific local pollution problems, always depending on the municipalities' authorization and strategy.

The presented scenario approach do not provide additional useful information from decision-making point of view, such as related health benefits, and an estimation of the implementation costs of the different measures. This information could be advantageous allowing selecting cost-efficient mitigation measures. Furthermore, the test of different emission scenarios is very time consuming due to computational requirements.

3 Applying Integrated Assessment Methodologies to Air Quality Plans: Two European Cases

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.

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I mainly contributed to RIAT+ Porto simulations, results analysis and manuscript writing. The Brussels simulations were performed by Peter Viaene in the framework of the APPRAISAL FP7 project.

3.1 Introduction

European Union Member States have in the last decade 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.*, 2012b; Carnevale *et al.*, 2011; Cuvelier *et al.*, 2007; Lefebvre *et al.*, 2011; Mediavilla-Sahagún & ApSimon, 2003). 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.*, 2016a). 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 Systems, which bring together air quality, health and cost-benefit aspects in the current assessment methodologies of 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 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 & 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, the setup of an IAM tool and the evaluation of its output, a state of the art guidance document on Integrated Assessment (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, 1999) 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.

3.2 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 (Karagulian & Belis, 2012; Viana *et al.*, 2008). 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.

3.2.1 The RIAT+ system

RIAT+ (Carnevale *et al.*, 2012a) 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 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 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 index, 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 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 the 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.

3.2.2 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 Figure 3.1.

Figure 3.1 - Location of the BCR (red zone) in Belgium.

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 (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 inTable 3.1.

Table 3.1 - List of measures considered for the BCR with their removal efficiency as % of the 2010 emission, and the yearly average NO_2 and PM10 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	SOx	VOC	PM2.5	PM10			
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	0.2	19.4	17.2	0	28.6	22.0	333
∑ **Traffic**	9.78	1.97	47.17	46.34	0.04	27.8	20.7	312
7 Boiler maintenance	2.20	0.19	2.25	2.5	1.51	28.6	22.0	333
8 Exemplary buildings	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	0.3	28.6	22.0	333
∑ **Heating**	3.51	0.31	3	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

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.

3.2.2.1 Design of the experiment

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 × 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) (URL8) for the measurement stations inside the model domain. For the validation, the methodology proposed by FAIRMODE (URL9) was adopted (Pernigotti *et al.*, 2013; Thunis *et al.*, 2013). More details on the validation and results can be found in (APPRAISAL, 2015a).

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 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 3.2. 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.

Table 3.2 - List of the emission reduction scenarios obtained combining B, H, L scenarios.

Scenarios	NO_X	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

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 Index (AQI) that were related to emissions by the ANN were:

- 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 Figure 3.2 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.

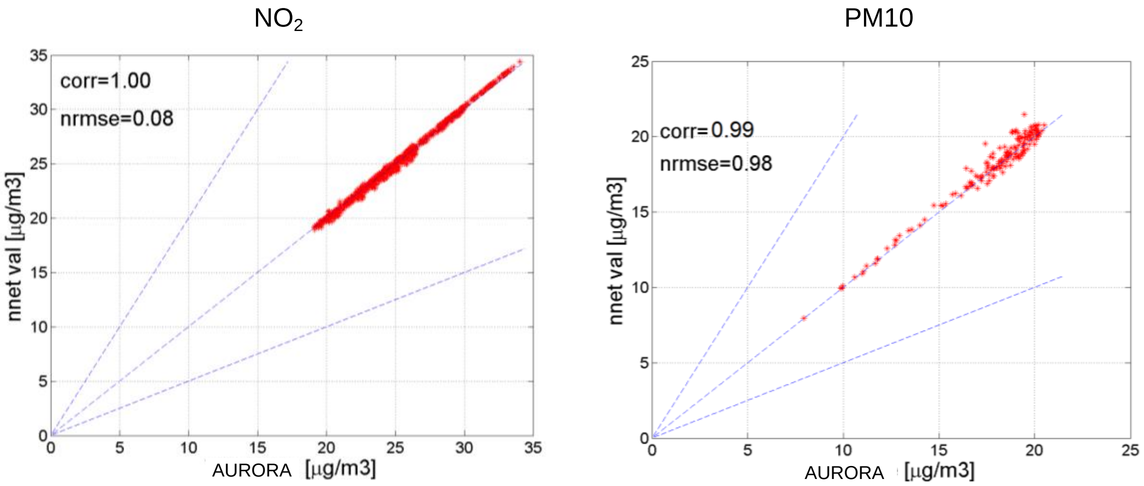


Figure 3.2 - NO_2 (left) and PM10 (right) scatter plots for the validation of the ANN outputs vs the AURORA outputs.

As can be seen from these scatter plots (Figure 3.2), 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.

3.2.2.2 Results obtained with RIAT+

Once the ANN have been trained, they can be used to obtain results for the different measures/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. Figure 3.3 shows the spatial distribution of the YOLL, as visualized by RIAT+, for CLE2020, and considering the implementation of all proposed traffic and non-industrial heating measures. Table 3.1 presents for each measure considered the yearly average NO_2 and PM10 concentrations as well as the health costs.

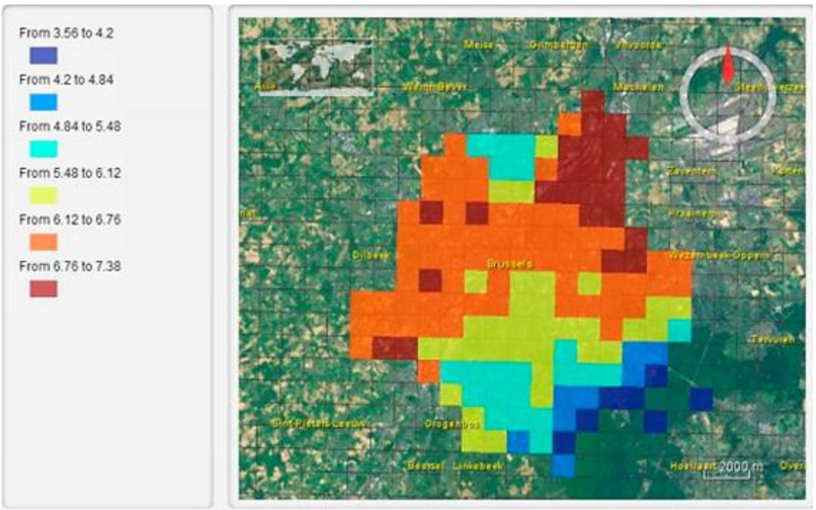


Figure 3.3 - Years of life lost (YOLL) expressed in months over the study domain for year 2020 when all proposed traffic and non-industrial heating measures are implemented.

The spatial distribution of the YOLL values (Figure 3.3) 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.

From Table 3.1 it can be seen that the yearly average NO_2 and PM10 concentration will decrease, respectively, by 0.9 µg/m^3 (4%) and 1.5 µg/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 3.1. 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.

3.2.3 Porto optimization approach

The Great Porto Area is a Portuguese NUTS3 (Nomenclature of Territorial Units for Statistics) sub region involving 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, 2012b) and were used to calculate population exposure to PM10.

Figure 3.4 shows the location of the Greater Porto Area in Portugal and in the northern region of Portugal.

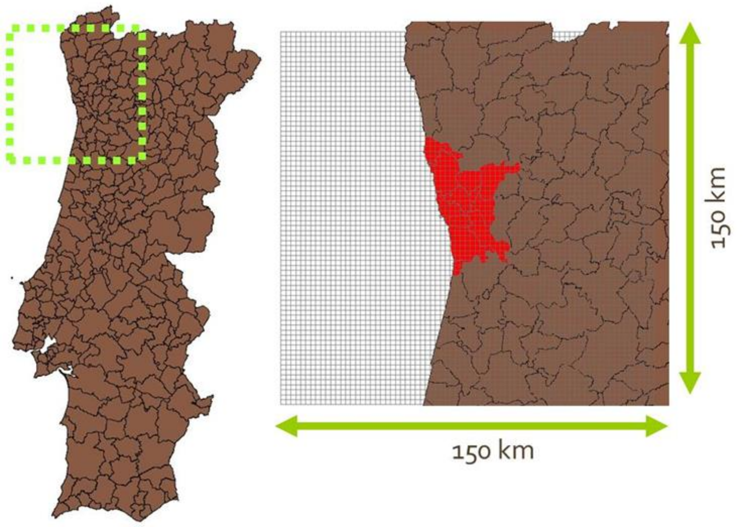


Figure 3.4 - Location of the Great Porto Area in Portugal and in the Northern Region of Portugal.

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.*, 2012b). 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 (URL6), 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 (SNAP 2), efficient dedusters (SNAP 3 and SNAP 4), and low-emission vehicles (SNAP 7). 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.

3.2.4 Design of the experiment

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 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 3.3 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 the table has been modified considering the different features of the CTM applied for the simulations (in this case not considering NH_3 emissions).

Table 3.3 - List of the emission reduction scenarios obtained combining B, H, L scenarios.

Scenarios	PAD emissions			
	NO_X	VOC	PM	SO_2
0	B	B	B	B
1	L	L	L	L
2	H	H	H	H
3	H	L	L	L
4	L	H	L	L
5	L	L	H	L
6	L	L	L	H
7	H	H	L	L
8	H	L	H	H
9	H	L	L	H

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 (URL7). 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. Figure 3.5 presents the ANN performance for the annual PM10 concentration value.

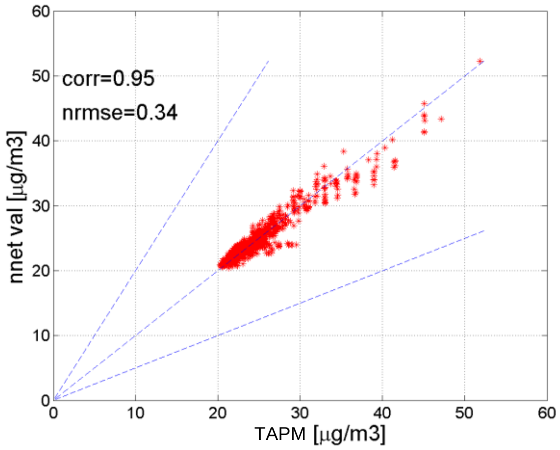


Figure 3.5 - ANN system performances evaluated in terms of scatter plot between ANN and TAPM results for PM10.

The scatter plot in Figure 3.5 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.

3.2.5 Results obtained with RIAT+

RIAT+ was applied in the multi-objective optimization mode and Figure 3.6 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.

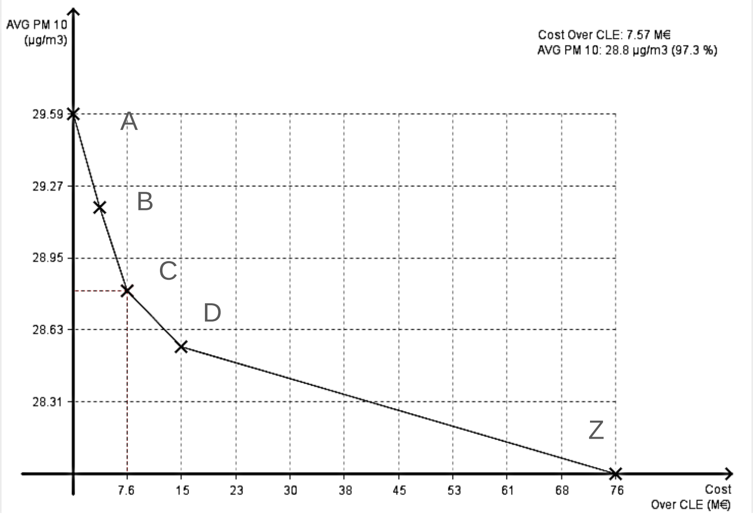


Figure 3.6 - Pareto curve for the optimization of PM10 yearly mean concentrations.

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, Figure 3.7 presents the emission reduction by EMEP/CORINAIR macrosector 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 Organic Compounds (VOC). Road transport (SNAP 7) and other mobile sources and machinery (SNAP 8) could also contribute to this reduction of PM concentrations.

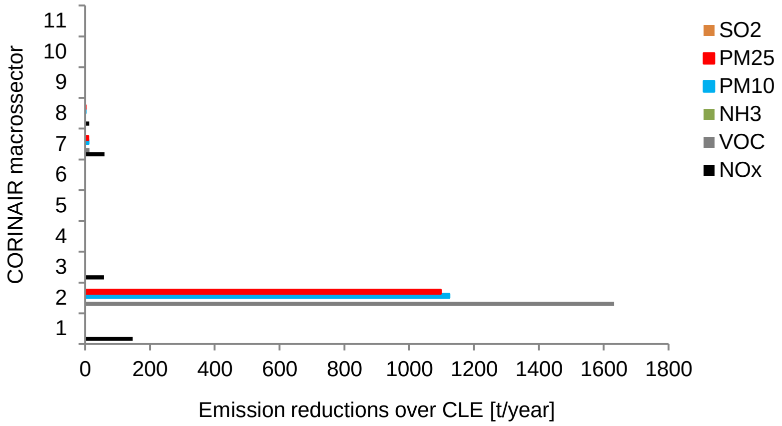
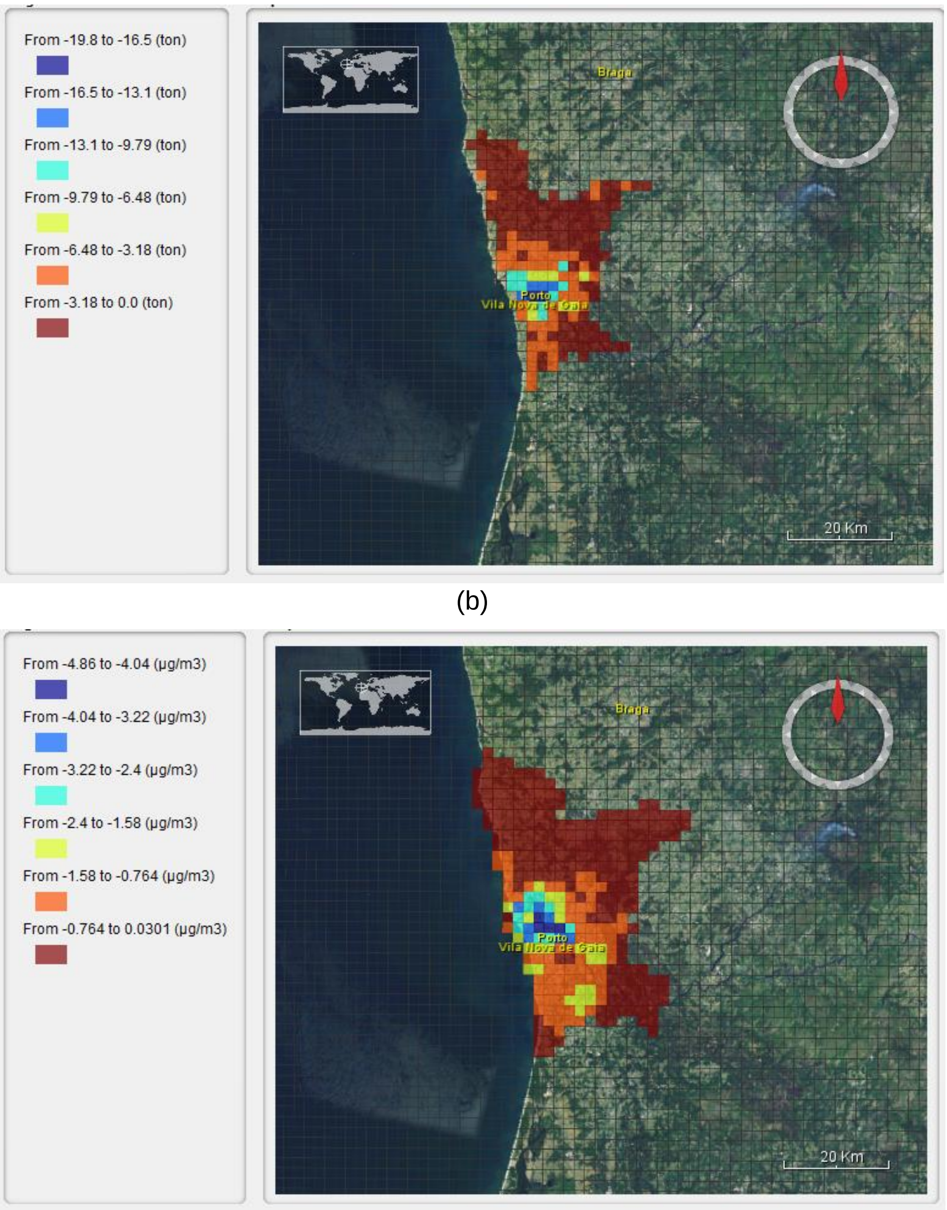


Figure 3.7 - RIAT+ emission reductions (t/year), by CORINAIR macrosector corresponding to point C of the Pareto curve.

As shown in Figure 3.7 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.* (2012b) 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 macrosector is the second most important in terms of PM10 emissions, after macrosector 4 (industrial processes), in the Great Porto Urban area.

Figure 3.8 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 µg/m^3) are expected over the Porto municipality where the population density is higher.

(a)



(b)

Figure 3.8 - RIAT+ emission (t/year) (a) and concentration (µg/m^3) reductions for the point C of the Pareto curve (b).

Finally, Figure 3.9 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 substantially 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.

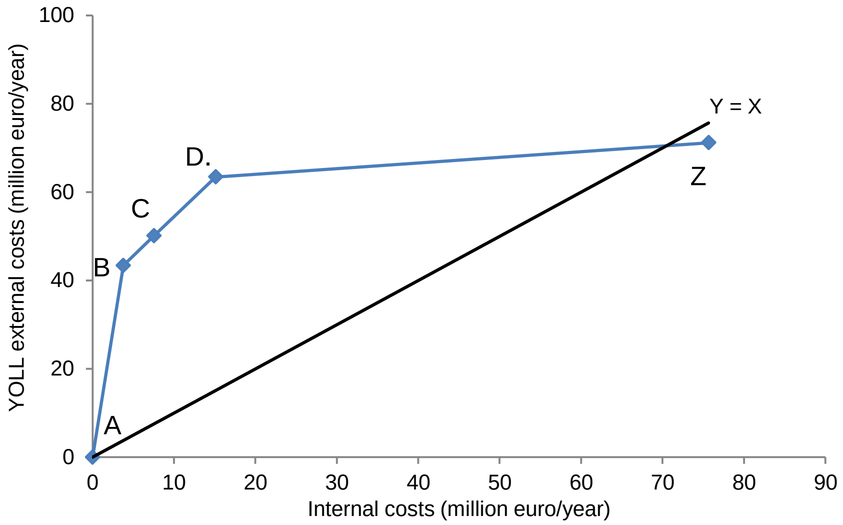


Figure 3.9 - External costs vs internal costs.

As shown in Figure 3.9 the external costs are always higher than the internal costs (except point Z). This fact points out that, acting on emission control to reduce PM10 concentrations is greatly beneficial from a socio-economic point of view.

3.3 Conclusions

In this chapter we have presented the implementation of an existing comprehensive IA system (RIAT+) for two different test cases, the Porto Region and the 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. CTM), 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. Furthermore, technological measures may affect more than one pollutant at same time, subsequently optimization considering multi-pollutant should also be considered.

4 Optimal Air Quality Policies and Health: a Multi-objective Nonlinear Approach

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 $\mu g/m^3$, 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.

This chapter was published as:

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4.1 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 of 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 (2015; 2016). 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 (Borrego *et al.*, 2012b; CCDR-LVT, 2006; CCDR–N, 2007; 2010).

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).

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.*, 2012a; 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.*, 2016a; Relvas *et al.*, 2016; Thunis *et al.*, 2016b). Within the first approach 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.

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 policymaking 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 & ApSimon, 2006), FRES-Finland (Karvosenoja, 2008), LEAQ (Zachary *et al.*, 2011), RIAT+ (Carnevale *et al.*, 2012a), EVA (Brandt *et al.*, 2013) or AERIS (Vedrenne *et al.*, 2014; Vedrenne *et al.*, 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.*, 2012b). 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.*, 2012a), providing useful information to policymakers. Recently it has been applied to Brussels (Belgium) and to Porto (Portugal) (Miranda *et al.*, 2016b). 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.

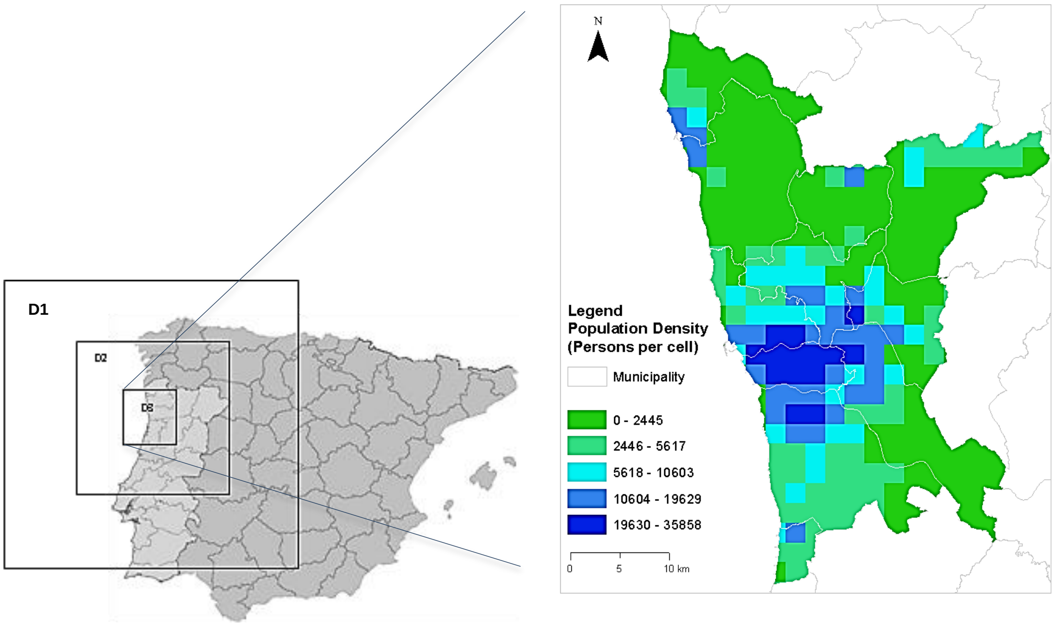
The main goal is to identify the most cost-effective mix of local policies for reducing human exposure to both PM10 and NO_2, being able to answer questions like “in which sector(s) will our investments be more effective?”, “how much will we benefit in terms of health (avoided costs) from our investments?”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

This chapter is organized as follows. Section 4.2 describes the case study, Section 4.3 presents the RIAT+ setup, Section 4.4 shows its application focusing on the Pareto curve calculation and on the analysis of results. Finally, the conclusions (Section 4.5) address the benefits of this kind of approach.

4.2 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 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; Borrego *et al.*, 2012b). 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 Figure 4.1, has been considered as an area in which air quality improvement measures should be focused. It represents the priority area for air quality (Policy Application Domain – PAD). This important Portuguese sub region is highly industrialized and the population ascend to 1,200,000 inhabitants (INE, 2012b).



(a) (b)

Figure 4.1 - The Porto Urban Area: (a) The simulation domains used in the TAPM modelling application; (b) population density in the Porto Urban Area.

In Table 4.1 the total annual emissions in the Porto Urban Area, corresponding to the most updated national emission inventory report (APA, 2010), are listed.

Table 4.1 - Annual Porto Urban Area emissions (2009), for the different CORINAIR macrosectors (APA, 2010).

ID	*CORINAIR macrosector*	*NO_X*	*VOC*	*NH_3 (t/year)*	*PM10*	*PM2.5*	*SO_2*
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	16712	0	0	0	0

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 (URL6), 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 Section 4.3).

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.

4.2.1 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 non-linear 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 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 4.2) 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 4.2) 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.

4.2.2 Design of Experiments

The design of experiments 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.

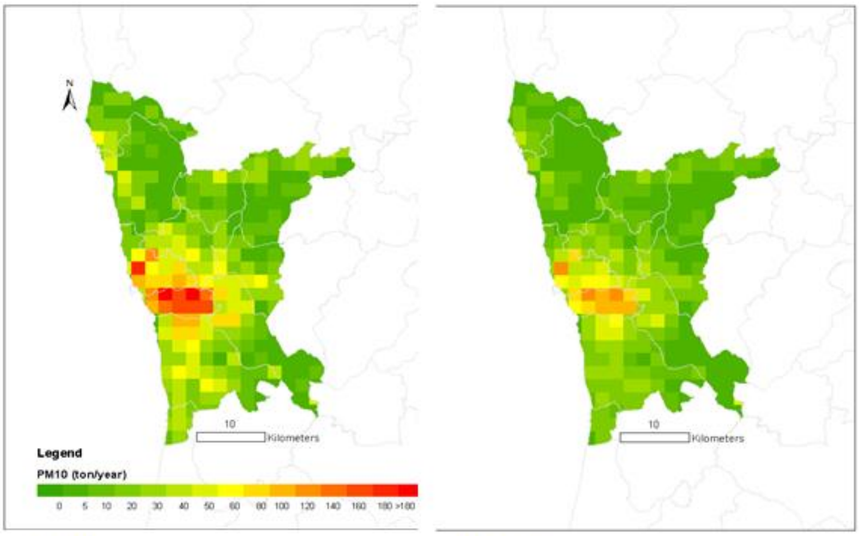
The 10 reduction scenarios were created, for each precursor emission, considering three emission levels, which were combined: the 2020 CLE (Current Legislation Emissions) + 15% (upper bound), the 2020 MFR (Maximum Feasible Reduction) − 15% (lower bound) and the average between these two extremes, to 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 4.2 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).

Table 4.2 - 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.	-21.0	-49.7

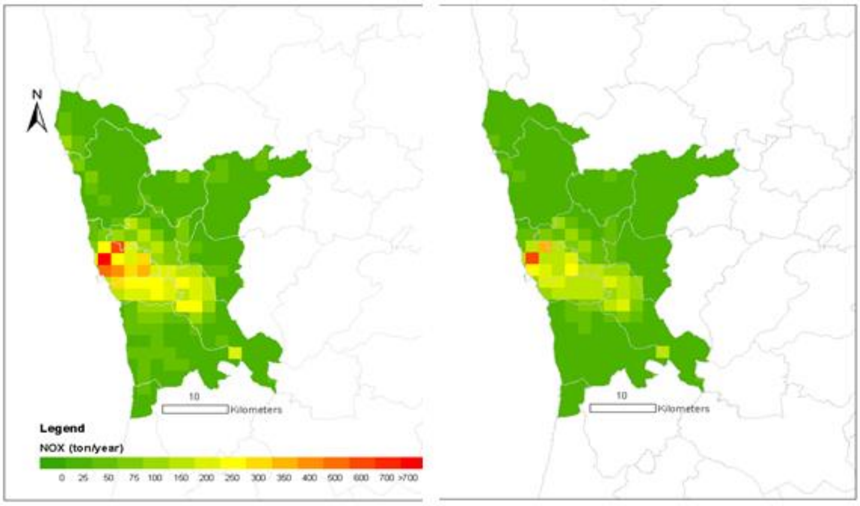
For SO_2 emissions under scenario 1, an increase is expected in relation to the base case. This scenario is obtained considering the evolution of 2009 emissions under the CLE2020 scenario plus 15%. This SO_2 increase can be explained by an emission increase on macrosector 3 (due to industrial growth) 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 Figure 4.2. For additional emission maps (PM2.5, NH_3, SO_2 and VOC) please see Appendix A.



(a) CLE2020

(b) MFR2020



(c) CLE2020

(d) MFR2020

Figure 4.2 - 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 yr^{-1}.

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.

4.2.3 Chemical transport model simulations

The air quality model simulations have been performed with “The Air Pollution Model” (TAPM) (Hurley *et al.*, 2005), developed by the 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 Figure 4.1). 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.

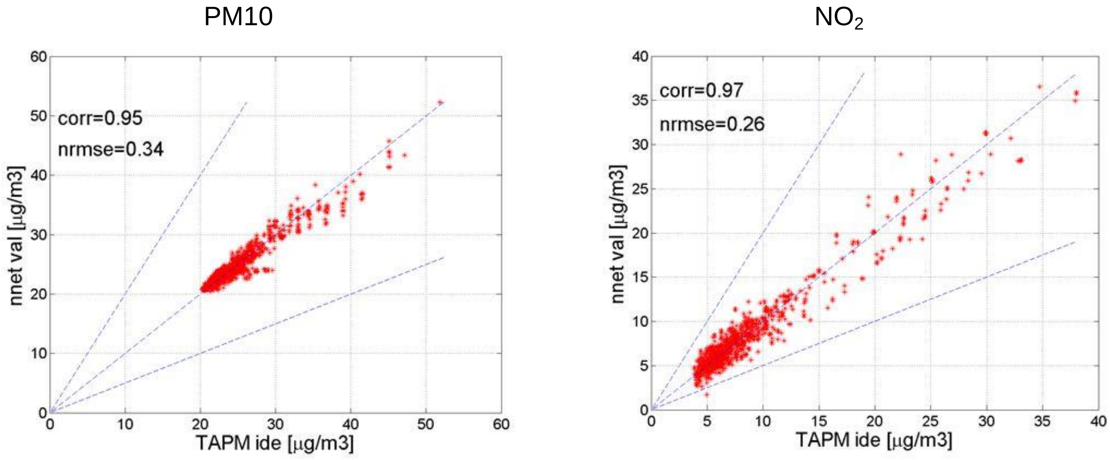
Modelled concentrations by TAPM were compared against measurements from the Portuguese Agency for the Environment monitoring network (URL7). Monitoring stations inside the domain were considered for the model validation, which was based on the FAIRMODE methodology. Details on this validation, namely performance skills, can be found in (APPRAISAL, 2013). Moreover, TAPM was the used model in the scope of Northern Region AQP (Borrego *et al.*, 2011; Borrego *et al.*, 2012b) 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 Table 4.2.

The selected ANN structure considers input coming from 4 contiguous quadrants, thus considering prevalent wind directions. Different literature shapes/configurations can be used (Carnevale *et al.*, 2012b; 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 Appendix B.

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 this 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 Appendix C. The scatter plots in Figure 4.3 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 highlights that all points are very close to the bisecting line, even if the identified neural networks slightly underestimate the PM10 index.



(a) (b)

Figure 4.3 - 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.

The Normalised 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.

4.3 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 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 PM10;
III. a joint index composed by NO_2 and PM10 assuming equivalent importance (weight) in the optimisation 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 (2013).

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 vehicles 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 0.20 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 4.3.

II. Electric Taxi Programme, implies the replacement of 500 diesel taxis from a total of 3217 (see Appendix D) 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 kilometres driven by vehicle by year was assumed. The resultant emission reduction is shown on Table 4.3.

III. The Bike Programme is part of the National Reform Programme, aims to make available 6000 new bicycles on free shared systems by 2020 in Portugal. The program incentives students, municipal staff and general public 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 kilometres driven by vehicle by year) is shown on Table 4.3.

Table 4.3 -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

4.4 Results and discussion

Figure 4.4 and Figure 4.5 show NO_2 and PM10 annual concentration values spatially averaged over the entire simulation domain for the different optimal solutions.

We can see from Figure 4.4 and Figure 4.5 the policy outcomes computed with the air quality indexes described above. Annual averaged NO_2 concentrations obtained with an optimization focused on NO_2 only (Figure 4.4, 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).

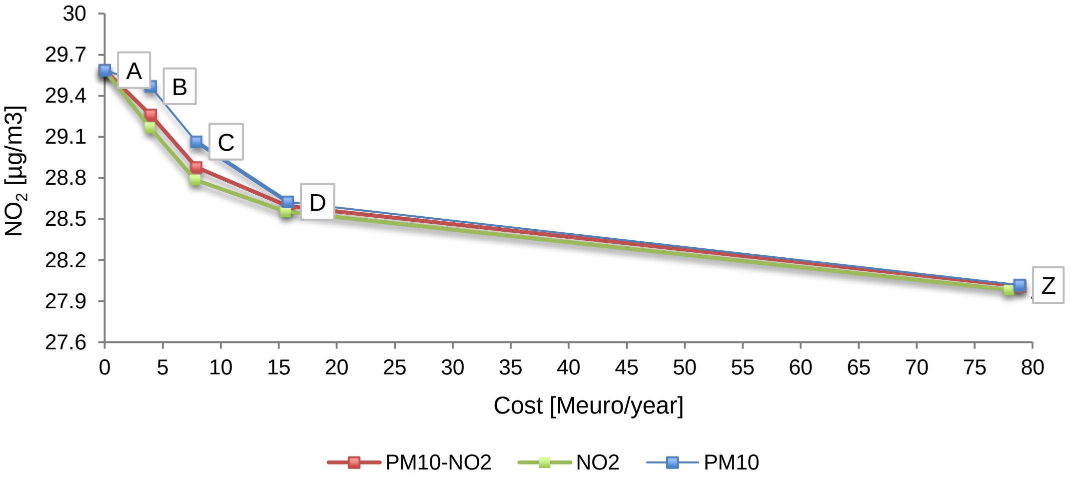


Figure 4.4 - Pareto optimal policies computed considering the three selected optimizations, with cost of policy implementation (x-axis) and NO_2 yearly average (y-axis). The green line corresponds to the NO_2 optimization, the blue line to the PM10 optimization, and the red line to the multi-pollutant case.

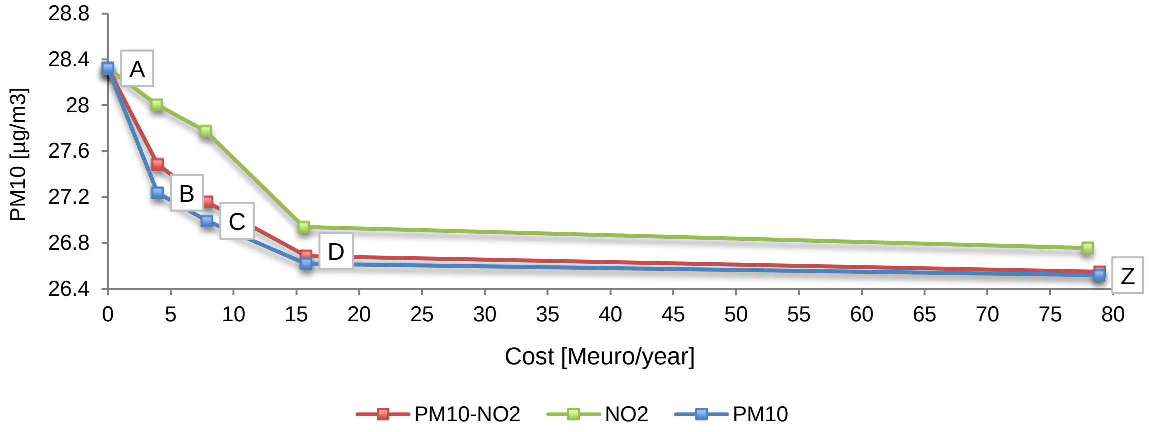
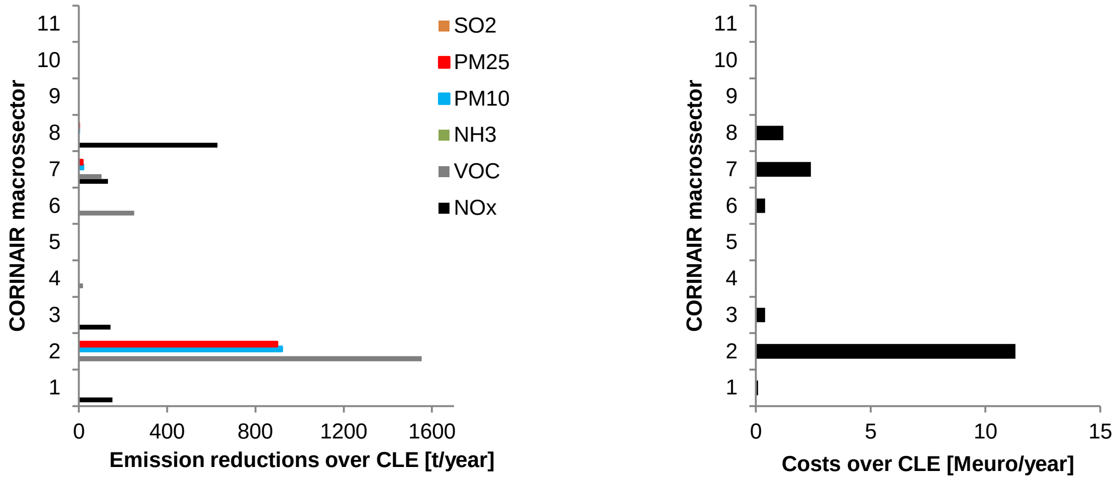


Figure 4.5 - Pareto optimal policies computed considering the three selected optimizations, with cost of policy implementation (x-axis) and PM10 yearly average (y-axis). The green line corresponds to the NO_2 optimization, the blue line to the PM10 optimization, and the red line to the multi-pollutant case.

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.

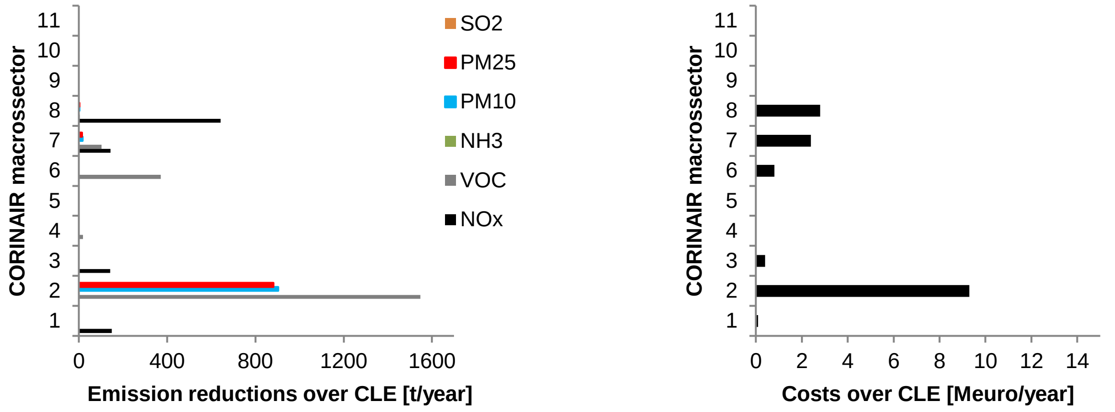
Figure 4.6 details solution D in terms of emission reductions and implementation costs beyond CLE, aggregated per CORINAIR macrosector. The left side panels show emission reductions beyond CLE, and the right side ones the cost beyond CLE, entailed by the optimal policy related to the point D of the previously illustrated Pareto curve. For the yearly NO_2 optimization (Figure 4.6 (c) and (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 macrosector 2, some chemical reactions involving VOC, NO_X and O_3 may be responsible by this outcome.

PM10 / NO$_2$ (optimization)



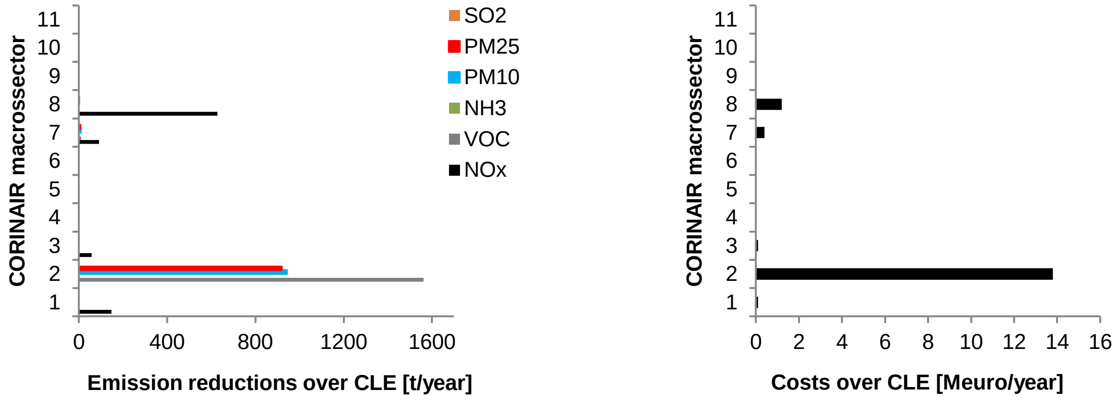
(a) (b)

NO$_2$ (optimization)



(c) (d)

PM10 (optimization)



(e) (f)

Figure 4.6 - Emission reductions (left) and costs beyond CLE (right), corresponding to solution D, for (a, b) joint NO$_2$ and PM10 optimization; (c, d) NO$_2$ optimization; (e, f) PM10 optimization.

On the other hand, actions (i.e. emission reductions) are more efficient in macrosectors 2, 7, and 8 for PM10 (Figure 4.6 (e), (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 (Figure 4.6 (a), (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.

As we can see from Table 4.3 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 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” measures 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.

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 $\mu g/m^3$ and a PM10 concentration reduction of 1.7 $\mu g/m^3$ over Porto Urban Area domain. Higher concentration reductions are expected over the Porto municipality where the population density is higher.

Figure 4.7 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 $\mu g/m^3$ (the air quality limit value). In the case of PM10 the air quality limit value of 40 $\mu g/m^3$ will continue to be exceeded, mainly in Porto municipality.

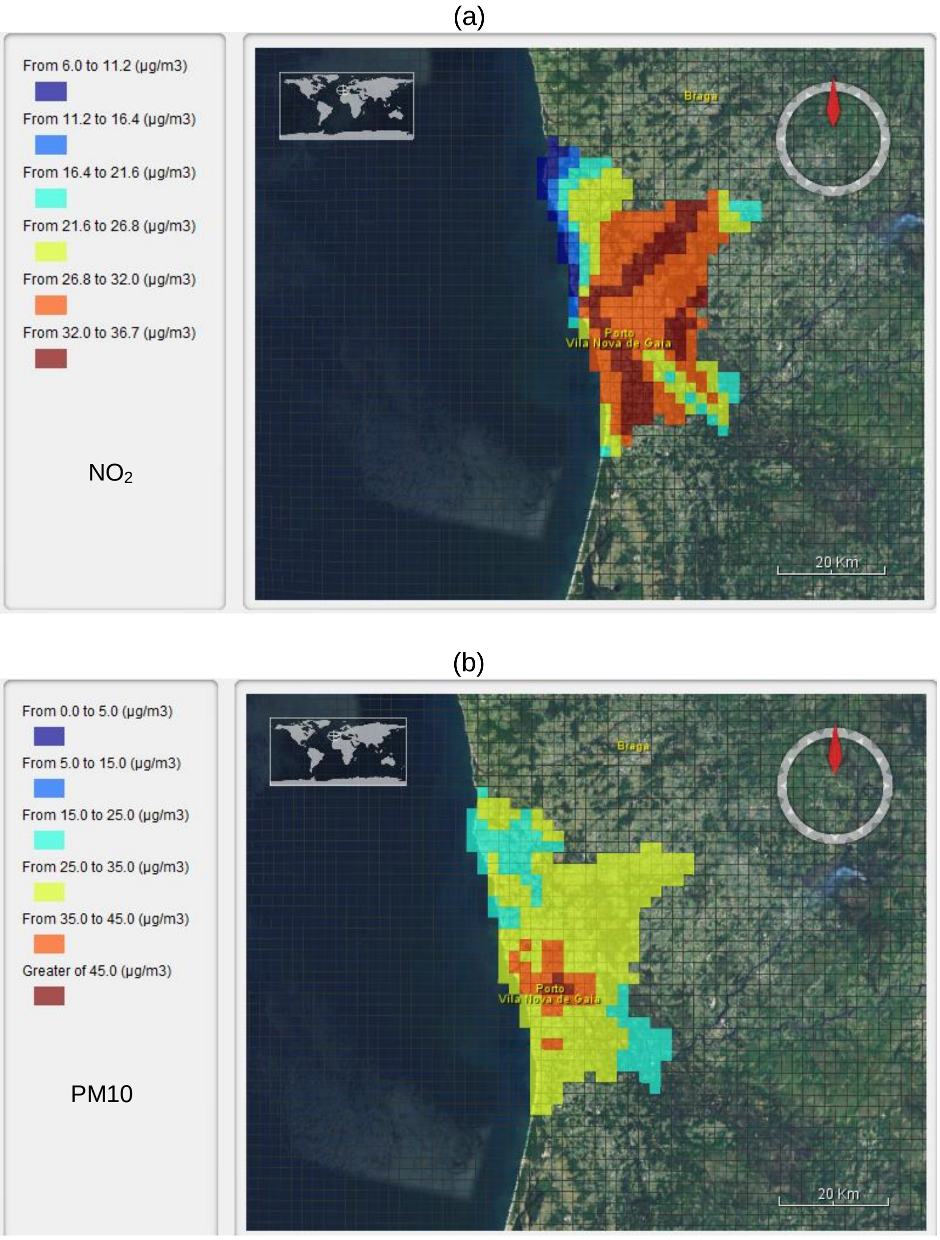


Figure 4.7 - RIAT+ NO_2 concentration ($\mu g\ m^{-3}$) (a) and PM10 concentration ($\mu g\ m^{-3}$) (b) for the point D of the Pareto curve.

RIAT+ can also produce health maps such as years of life lost (YOLL), using calculated air 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 & 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 the Pope epidemiologic study (Pope *et al.*, 1995) 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. Figure 4.8 shows the spatial distribution of the difference between YOLL estimated for the base case and considering the implementation of the measures shown on Table 4.3 (Solution D).

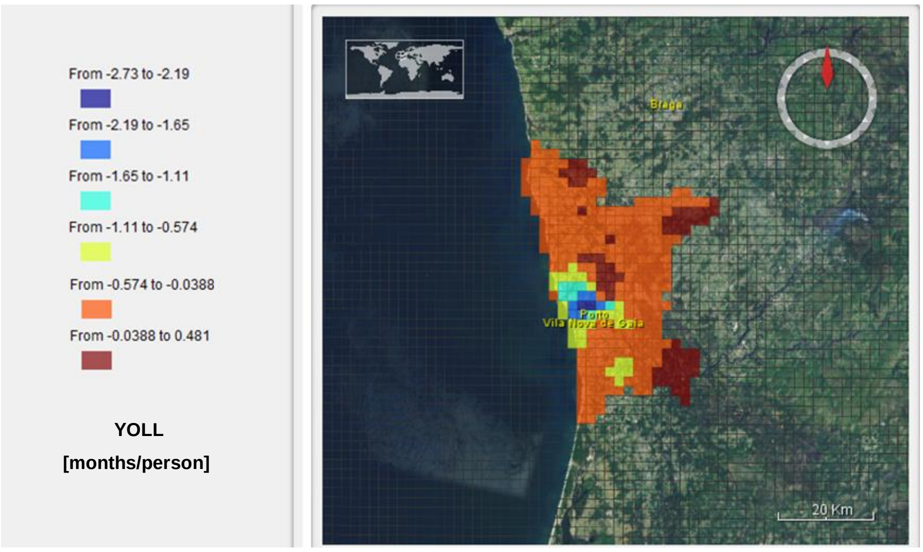


Figure 4.8 - Difference between years of life lost (YOLL) expressed in months/person over the study domain estimated for the base case and considering point D of joint NO_2 and PM10 optimization.

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 Figure 4.1 and Figure 4.2).The simulated concentration values at 2 km cell level, however, mask the presence of high-concentration hotspots at the local 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.

4.5 Conclusions

Optimization techniques can be used to contribute to a more effective solution of the problem of pollutant concentration reduction in atmosphere. However, they need fast surrogate models that link precursor emissions to pollutant concentrations. 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 set 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 realise that concentration reductions of both pollutants can be obtained with similar costs to those focused only on one pollutant. However, optimised results depend on the provided specific set of emissions, abatement measures, and abatement costs. Thus, more reliable, realistic and representative the underlying information is, 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 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 an important air quality improvement.

RIAT+ can give in approximately 5 minutes a 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 same 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 an 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.

5 Application of the DPSIR Framework to Air Quality Approaches

Abstract

Current air quality legislation in Europe will lead to substantial air quality improvements, but without further emission control efforts the most critical hotspots will persist, with important impacts on the environment and human health. Integrated Assessment Models (IAM) can be applied at local and regional scale to support the assessment of mitigation opportunities and decision-making process. The mitigation measures need to be sustainable, and subsequently, social, economic and environmental factors need to be balanced. This paper proposes the use of the well-known DPSIR framework, which is composed by Driving forces, Pressures, State, Impacts and Responses. The urban area of Porto (Northern Portugal) is the selected case study and DPSIR radar charts are used to easily compare different IAM approaches and help researchers and policy-makers to achieve the objective of air quality improvement. Results indicate that the MAPLIA system based on scenario approach and the RIAT+ system based on optimization approach provide more detailed and comprehensive information, namely concerning health (Impacts), then the previously designed Porto's Air Quality Plans (AQP).

This chapter was submitted as:

Relvas H., & Miranda, A. I. (2018). Application of the DPSIR Framework to Air Quality Approaches. *Air Quality, Atmosphere & Health. (accepted)*

5.1 Introduction

Conceptual models, which consist of diagrams and associated descriptions, are a useful way of summarizing information not only for presentation and communication but also for the analysis of alternative decisions (Brudvig *et al.*, 2017; Joffe & Mindell, 2006). According with Bradley (2015) these models also identify the bounds and scope of the system of interest, the connections of processes across disciplinary frontiers, and contribute to improve communication (e.g. between scientists and decision-makers).

A key current conceptual framework, DPSIR (Driving force–Pressure–State–Impacts–Response) (Figure 5.1) employed by the European Environment Agency (EEA, 1999) is now overspread. Studies related with analysis of marine environmental problems and coastal management (Gari *et al.*, 2015; Goble *et al.*, 2017; Lewison *et al.*, 2016; Zhang & Xue, 2013), green infrastructure planning (Spanò *et al.*, 2017), climate change (Bär *et al.*, 2015), or emissions and air quality (Diab & Motha, 2007; Guariso *et al.*, 2016; Zhou *et al.*, 2015), can be easily found in literature.

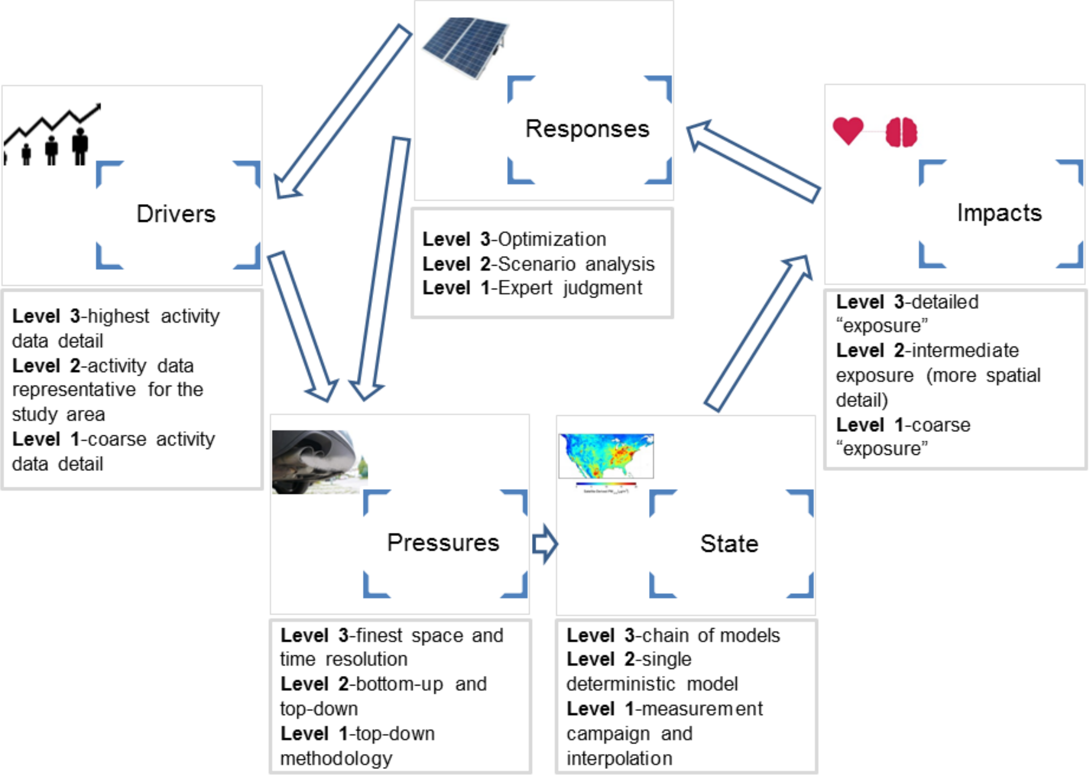


Figure 5.1 - DPSIR blocks and associated levels of detail or complexity.

Despite the air quality improvements occurred in the last decades, air pollution continues to be a risk to health in the world, and in Europe in particular. Between 2013 and 2015, a substantial proportion of the urban population in the EU-28 was exposed to concentrations of certain air pollutants above the EU limit (16-20% relatively to particulate matter (PM10), and 7-9 % to nitrogen dioxide (NO_2) (EEA, 2017).

The successful improvement of air quality in polluted areas and the formulation and implementation of Air Quality Plans (AQP), mandatory by the Air Quality Directive (2008/50/EC), requires an integrated view and the management of several aspects, such as the assessment of the emission sources, the causes of that emission, and the possible consequences. The main components that have to be included in an AQP were summarized by Miranda *et al.* (2015). Furthermore, it is necessary to evaluate the different mitigation options, and its potential societal benefits (including economic). The success of these improvement measures depends on the effectively engagement of air quality policy-makers and stakeholders, because their inputs and agreement are critical in order to operationally implement local or regional actions.

There is nowadays a growing interest in Integrated Assessment Models (IAM) and tools for local and regional scale. IAM can support the development of AQP and the decision-making processes. They can be broadly grouped into two main categories: (i) the scenario analysis (Aggarwal & Jain, 2015; Guo *et al.*, 2016; Kansal *et al.*, 2009; Miranda *et al.*, 2016a; Vedrenne *et al.*, 2014), and (ii) the optimization analysis (Amann *et al.*, 2011; Relvas *et al.*, 2017). More details and an overview of current regional and local scale air quality modelling practices in Europe can be found in Thunis *et al.* (2016a).

The DPSIR framework can help researchers and policy-makers to compare different IAM options, in order to achieve the objective of air quality improvement. According to APPRAISAL project outcomes (Thunis *et al.*, 2016a; Viaene *et al.*, 2016) the several components of an IAM can be related with the DPSIR framework. The DPSIR structure blocks can be described as: (i) DRIVING FORCES – the key activities that result in emissions; (ii) PRESSURES – the pollutant emissions; (iii) STATE – the air quality; (iv) IMPACTS – the consequences of the air quality for human exposure, health impacts and for environment; and (v) RESPONSES – the alternatives that are available to decrease the impacts. As suggested by Guariso *et al.* (2016), the different DPSIR blocks can be studied and classified according to the degree of detail or complexity used; this allows to compare more easily different IAM approaches. Figure 5.1 summarizes the attributed levels of detail or complexity relatively to each one of the DPSIR blocks.

Following this classification the urban area of Porto (Northern Portugal) was used as case study to demonstrate how DPSIR can help researchers and policy-makers to compare different IAM options. This chapter is divided into four parts: an initial where the Porto AQP are assessed through the DPSIR framework; the second part concerning two different IAM applications over Porto (scenario analysis and optimization), the third part presents a comparative summary, and the final part explores the current best practices.

5.2 Porto air quality plans within the DPSIR framework

In order to comply with the air quality standards set by the current Air Quality Directive (2008/50/EU), the Northern Region of Portugal developed AQP to reduce PM10 (CCDR–N, 2007) and NO_2 (CCDR-N, 2011). Both were developed adopting a similar approach, which is based on scenario analysis. Despite the achieved improvement to which the economic and financial crisis (2008-2014) contributed (Monteiro *et al.*, 2017), air quality remains an important issue in Portugal, and in 2014 and 2015 exceedances to the annual limit value of NO_2 (in 2014 and 2015), the daily limit value for PM10 (in 2014 and 2015), and the annual limit value for PM10 (in 2015) were registered. The number of people who die annually with respiratory diseases and COPD (Chronic Obstructive Pulmonary Disease) still is high (see Figure 5.2).

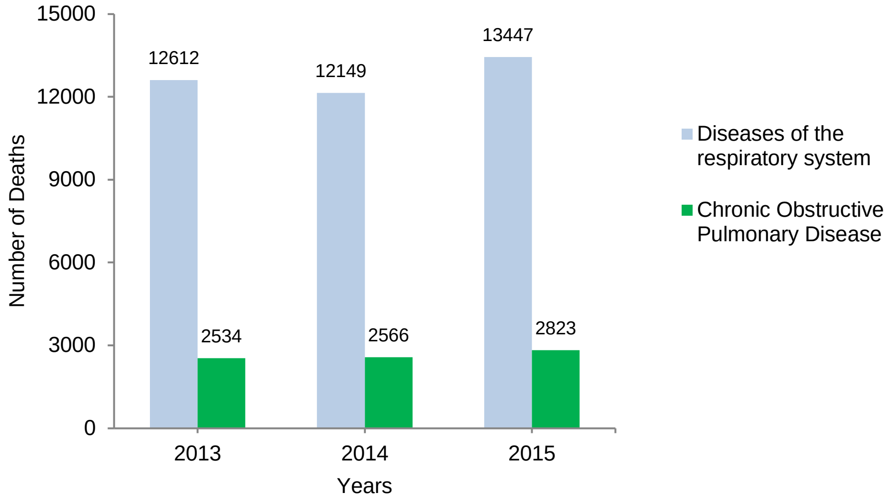


Figure 5.2 - Number of deaths by death cause. (Source: Statistics Portugal - Mortality by causes of death).

Aiming to better understand where designed AQP were not well developed, the DPSIR scheme with the different levels of complexity (Figure 5.1) was used to assess the AQP applied methods. The radar chart in Figure 5.3 represents a graph computed for Porto AQP. Since the same methodology was used for both Porto AQP, just one radar plot is shown.

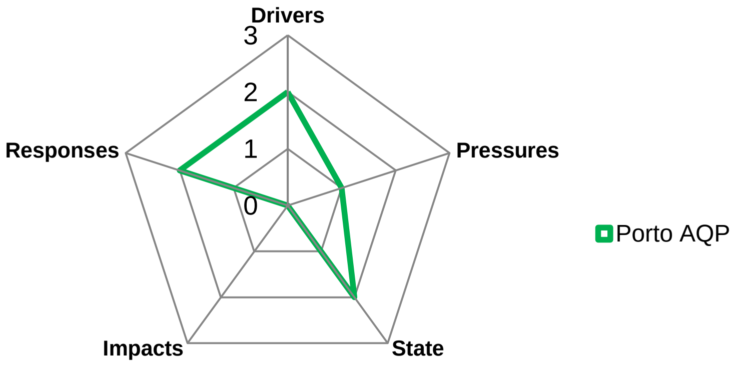


Figure 5.3 - Radar charts for Porto AQP (3=high; 2=medium; 1=low; 0= not considered).

In general, the AQP for Porto reached the DPSIR blocks in a low to medium level of complexity. In terms of DRIVERS, the level is medium because the used emission factors and activity data (e.g fuel consumption) are representative of the study area. Fuel consumption (gas, liquid or solid) by municipality was considered. Concerning PRESSURES, the low level is explained by the application of a top-down approach to estimate emissions instead of combined approaches (bottom-up and top-down). Moreover, only the level 1 SNAP (Selected Nomenclature for Air Pollution) (EMEP, 2013) was considered. According to SNAP nomenclature, source-emissions are classified among three levels of detail: (i) macrosectors (SNAP level 1), (ii) sectors activity (SNAP level 2), (iii) activity (SNAP level 3).

The STATE level of complexity is medium, mainly because only one air quality model was used, the Air Pollution Model (TAPM) (Hurley et al., 2005). The application of other air quality models, for instance local scale models, could be important, allowing for a better identification of the impacts of mitigation measures, especially those related to traffic.

In the development of Porto`s AQP, the human health effects were not considered, thus the detail level of the IMPACTS assessment block is zero. Despite this, the knowledge of the health impacts (and consequent external costs) from the different emission reduction scenarios is essential in helping the decision-makers, because with this information they can make more deliberate, thoughtful decisions in order to protect the population. Consequently, even if the complexity of the approach is higher, the application of a methodology to estimate external costs (e.g. ExternE (Bickel & Friedrich, 2005)) should be considered.

The level of complexity is medium in relation to RESPONSES. The scenario analysis methodology, performed by means of TAPM, was used instead of an optimization approach. The list of measures was defined based on a close contact with stakeholders, in particular the municipalities, and their impact on air quality simulated. The optimization approach would allow selecting responses based on multi-objective analysis, including the decision process costs and benefits of different improvement strategies.

5.3 Applying DPSIR to Integrated Assessment Modelling

In order to better support the decision-making process, IAM should be applied with the maximum possible level of detail. However, a higher level of detail in the different DPSIR blocks implies the need of highly detailed input data and models. This leads to higher computational and human expert demands. In some cases, because blocks are interconnected, the detail level of a depending block is dictated by the low detail of previous blocks (Guariso *et al.*, 2016).

Two IAM approaches were applied to Porto: (i) the MAPLIA system based on scenario approach (Duque *et al.*, 2016; Miranda *et al.*, 2016a) and (ii) the RIAT+ system based on optimization approach (Miranda *et al.*, 2016b; Relvas *et al.*, 2017).

The MAPLIA system was designed to support the development of AQP requiring the definition and testing of specific local/regional abatement measures to reduce PM10 and NO_2 level in the air. The system allows evaluating the effects of previously selected improvement measures in terms of internal costs (due to the implementation of control measures), emissions, air quality, health impacts and associated external benefits (i.e. avoided external costs). Its application to the Porto Urban Area included emissions, air quality, and health for a set of 15 scenarios based on combinations of four emission reduction measures. More details can be found in Duque *et al.* (2016).

The RIAT+ (Carnevale *et al.*, 2012a) is an IAM tool designed to help regional decision makers to select optimal air pollution reduction policies to improve the air quality at minimum costs. Both scenario analysis and optimization approaches can be selected within RIAT+. It is capable to deal with a multi-pollutant optimization problem and with technical and non-technical measures (Relvas *et al.*, 2017). The tool has already been applied to several European regions, such as Alsace (France) (Carnevale *et al.*, 2014), Lombardy (Italy) (Carnevale *et al.*, 2012a), Brussels (Belgium) and Porto (Portugal) (Miranda *et al.*, 2016b).

5.3.1 DRIVERS and PRESSURES: activities and emissions

The DRIVERS block concerns the development of activities (agriculture, residential combustion, road traffic, etc.), that depend on other variables, as economic growth, population, or education. It is the direct input to the PRESSURES block that describes the release of emissions into the atmosphere from different sources. These emissions are generally computed as the product between the activity data and a specific emission factor. In addition to national or regional emission inventories, emission data could also be based on European inventories, such as EMEP (Vestreng *et al.*, 2007) or TNO-MACC (Kuenen *et al.*, 2014).

Typically just a small portion of emissions belonging to a specific Core Inventory Air Emissions (CORINAIR) macrosector is affected by control measures (Vestreng *et al.*, 2004). According with Nagl *et al.* (2007) and Miranda *et al.* (2015) road traffic emissions (SNAP 7) were the focus of most European AQP followed by non-industrial combustion (SNAP 2) and industry (SNAP 3 and 4).

In the MAPLIA system the most updated national emission inventory report (APA, 2014), for the 2012 year, was used to develop the reference scenario. Point (SNAP 1), line (SNAP 7 main roads) and area sources (other macrosectors) were considered. Emissions were temporally disaggregated using hourly emission profiles per macrosector, and spatially disaggregated from national level to municipality level. In particular, in the case of SNAP 2 a bottom up approach was used, taking into account the wood consumption per district, the type of residential combustion equipment, and emission factors from the Portuguese Agency for the Environment (APA) (Miranda *et al.*, 2016a). Regarding SNAP 7, road traffic emissions were estimated applying the Transport Emission Model for Line Sources (TREM) (Borrego *et al.*, 2004) and using traffic counts, average vehicle speed, and statistical fleet data.

In the RIAT+ application activities and emissions projected to 2020 were disaggregated to 2 x 2 km^2 grid cells (see Figure 5.4) using spatial proxies (e.g. Corine Land Cover classes, resident population, area of permanent and temporary crops), accordingly to the specificities of each macrosector, and achieving the SNAP code level-3 detail. As required by RIAT+, information about fuels, number of animals, and other activity data of the area under study was linked to SNAP code level-3 detail. The main sources of statistical data were:

- INE – National Statistical Institute of Portugal - www.ine.pt
- DGEG - Directorate General for Energy and Geology – www.dgeg.pt
- AFN – National Forestry Authority of Portugal –www.afn.min-agricultura.pt
- CLC – Corine Land Cover provided by Environmental Agency of Portugal (APA)

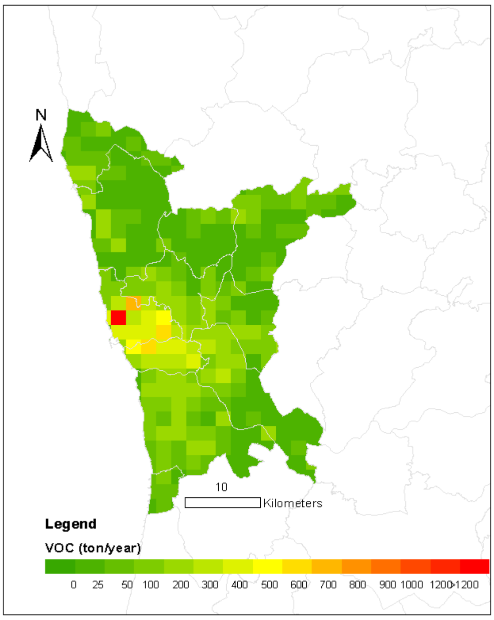


Figure 5.4 - Gridded 2 x 2 km^2 VOC emissions for 2020 in Porto Urban Area.

To calculate the cost-benefit of applying emission reduction measures with an IAM, information on costs and rates of application of technologies also have to be included. In the MAPLIA case expert judgement and local studies were used. In the RIAT+ application the GAINS model database was used (URL4). The database contains a large set of technologies that can be applied across the different emission sectors, and includes related costs, removal efficiencies and activity data.

The uncertainty related to the PRESSURES block can be indirect, due to the output of the DRIVERS block (missing/wrong relevant driving activities data), and direct, related to the emission inventory, to the spatial and temporal disaggregation and proxies used (Gioli *et al.*, 2015; Maes *et al.*, 2009).

5.3.2 STATE: Concentration

The STATE block describes the concentrations of the different air pollutants resulting from the emissions (PRESSURES). The different pollutants can be modelled by Chemical Transport Models (CTM) or monitored through fixed or mobile stations. Typically Eulerian based models are the most used because can be applied from the regional down to the local scale (Thunis *et al.*, 2016a). More details about air quality models used in Europe can be found in the EIONET Model Documentation System (URL2). The concentrations can be computed with different temporal and spatial resolutions and air quality indexes can also be calculated to deliver for example the number of PM10 daily exceedances or the annual mean of PM10.

The Air Pollution Model (TAPM) (Hurley *et al.*, 2005) is a 3D Eulerian model, which is composed by two modules that predict air pollution concentrations and meteorology (Figure 5.5). This model was applied in the MAPLIA and RIAT+ case studies, over the studied area (Porto Urban Area), with a

1 x 1 km^2 spatial resolution and with a 2 x 2 km^2 in the MAPLIA and RIAT+ studies, respectively, with 25 vertical layers (Duque *et al.*, 2016; Miranda *et al.*, 2016b).The model was validated using the measured data from the APA monitoring network (URL7).

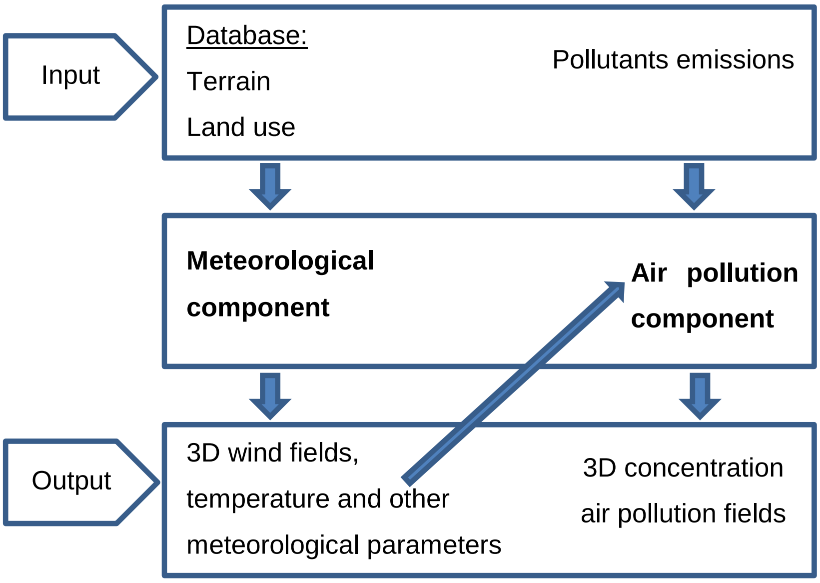


Figure 5.5 - TAPM model meteorological an air pollution scheme.

When considering multi-objective decisions problems CTM cannot directly be used in optimization algorithms due to their high computational time; thus statistical models called surrogate models are a good alternative (Carnevale *et al.*, 2008). In literature it is possible to find different surrogate model applications, from linear relationships (Clappier *et al.*, 2015), to polynomial surrogate models (Schöpp *et al.*, 1998) or Artificial Neural Networks (ANN) (Carnevale *et al.*, 2012b), that can be applied to different scales and target pollutants.

In RIAT+ case ANN were identified using the TAPM simulations in order to be possible to use the optimization algorithms, which make thousands of calculations to compute the best set of improvement air quality measures.

5.3.3 IMPACTS: Human health

The IMPACTS block is related to modifications of the environmental conditions, namely changes in the air quality (STATE). The different impacts can be discriminated among impacts on environment, human health, climate, and social. These impacts can then be economically evaluated, as suggested by the ExternE project (Bickel & Friedrich, 2005).

The IAM are frequently used to evaluate the change in population health status due to air pollution exposure. During the last decades, numerous epidemiological and toxicological studies reported a wide range of adverse health effects associated with short-term (hours, days) and long-term (months, years) exposure to air pollution (mainly particulate matter), and exposure-response functions were identified. The health indicators frequently used in IAM studies are premature mortality, morbidity, years of life lost due to premature mortality (YLL or YOLL) and disease-adjusted life years (DALY) (APPRAISAL, 2013).

In the case of the MAPLIA study, the impacts on human health were derived from TAPM simulations, using a 1x1 km^2 spatial resolution simulation grid and data regarding population age groups (INE, 2012b). The effects of short and long term exposure to pollutants such as PM10 and NO_2 were calculated using morbidity and mortality indicators.

Averaged annual avoided costs were calculated using health indicators per reduction scenario. To achieve this, duration of chronic effects of diseases for each health indicator were taken into account for the calculations. A typical MAPLIA output can be seen in Figure 5.6, which represents the health benefits of the implementations of the reduction scenarios regarding PM10 and $NO_{2.}$

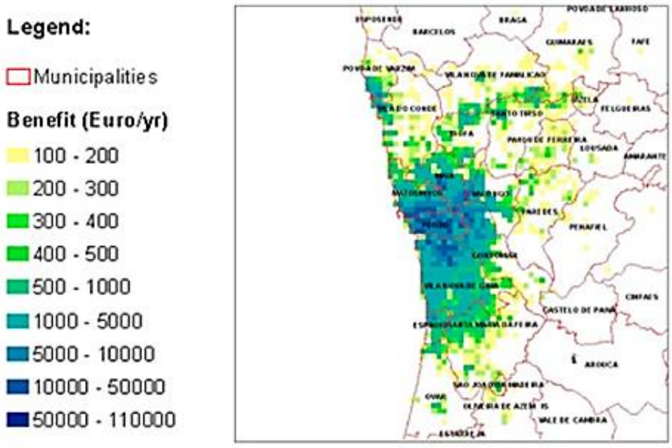


Figure 5.6 - MAPLIA estimated health impact expressed as economic value (Source: Miranda et al., 2016a).

In RIAT+ the ExternE approach (Bickel et al., 2005) has been applied to compute health impacts (mortality and morbidity), due to PM10 exposure. Information about population data by age group (INE, 2012b), mortality rate per age, and percentage of asthmatic per age class over total population were used.

Figure **5.7** shows a typical RIAT+ output: the difference between years of life lost (YOLL) [months/person] estimated for the base case and an optimal scenario.

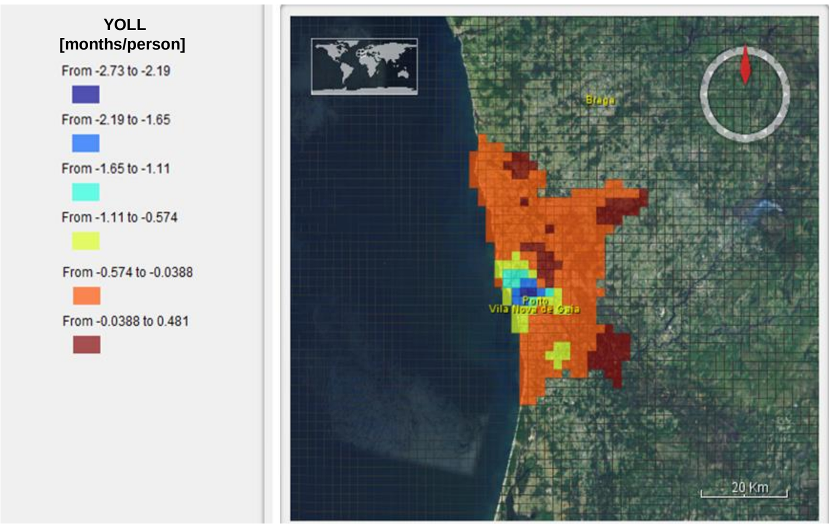


Figure 5.7 - Difference between years of life lost (YOLL) [months/person] estimated for the base case and optimal reduction scenario (Source: Relvas et al., 2017).

In both provided examples the impact on human health of Porto´s population is clear, even if the indicator used to express the impact is different. The sources of uncertainty related with health impact assessment can be summarized as follows: i) uncertainties in estimating the impact for each health outcome, ii) uncertainties in exposure assessment, ii) uncertainties related to the Relative Risks (RR).

5.3.4 RESPONSES: Decision framework

This RESPONSES block includes the regular approaches that can be used to select the emission abatement or other measures needed to efficiently reduce the impact of air pollution.

In the MAPLIA system expert judgement/opinion and scenario analysis were used to select air quality improvement measures. A number of predefined improving emission reduction scenarios (Implementing hybrid vehicles (S1), creating a Low Emission Zone (S2), improving residential combustion (S3), reducing production processes and industrial combustion emissions (S4)) was prepared and tested using the TAPM model (Duque *et al.*, 2016; Miranda *et al.*, 2016a). The system delivers costs associated to the emission reduction scenarios, both in terms of internal (for policy implementation) and external (health related) (see Table 5.1). In this case the level of complexity is medium.

Table 5.1 - Cost-benefit analysis of the reduction scenarios (Source: Miranda et al., 2016a).

Scenario	Implementation costs (M€·y^{-1})	Health benefits (M€·y^{-1})	Net benefit (M€·y^{-1})	Benefit-cost ratio
S1	2.0	1.5	−0.5	0.75
S2	0.8	1.8	1.0	**2.25**
S3	$3.8\text{x}10^{-2}$	$3.9\text{x}10^{-2}$	$1.0\text{x}10^{-3}$	**1.03**
S4	5.8	5.6	−0.2	0.97
S1+S3	2.8	3.3	0.5	**1.18**
S3+S4	6.5	7.4	0.9	**1.14**
S1+S2+S3+S4	8.6	8.9	0.3	**1.03**

In the RIAT+ application the optimization approach was used, in particular a multi-objective analysis. Therefore RIAT+ provides optimal air quality fields, i.e. concentrations levels, and optimal costs (internal and external costs) that can be achieved by applying the optimal emission reduction measures. RIAT+ also delivers the Pareto Curve (see Figure 5.8). The system provides the lists of optimal abatement measures and the related benefit (external costs), for different points of the curve. In this case the level of complexity is high.

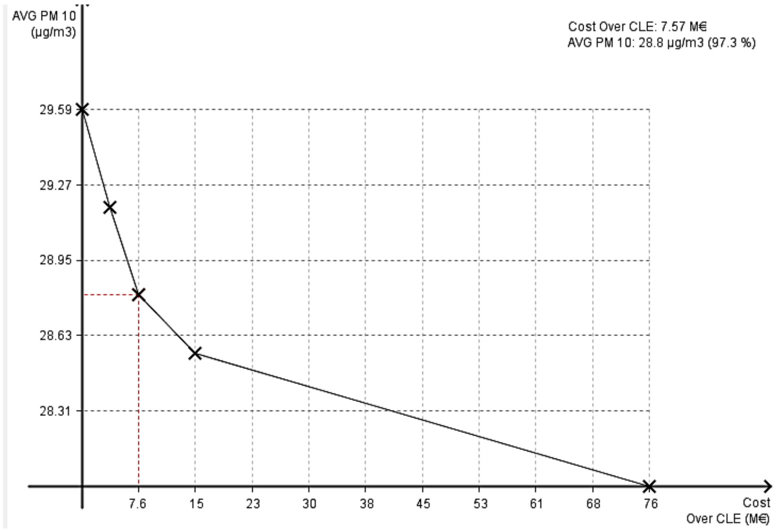


Figure 5.8 - RIAT+ Pareto curve for the optimization of PM10 yearly mean concentrations (Source: Relvas et al., 2017).

The uncertainties of previous bocks will have an effect on the decision taken, because a small change on costs or air quality index provided imply the choice of other solutions. While on air quality models it is possible to validate with field data, for an IAM this is not possible.

5.4 Comparative summary

Aiming to comparatively asses the performance of the AQP approaches within the DPSIR framework, Figure 5.9 summarizes the level of detail, for each DPSI
R block, and for Porto AQP and for both Porto´s IAM approaches.

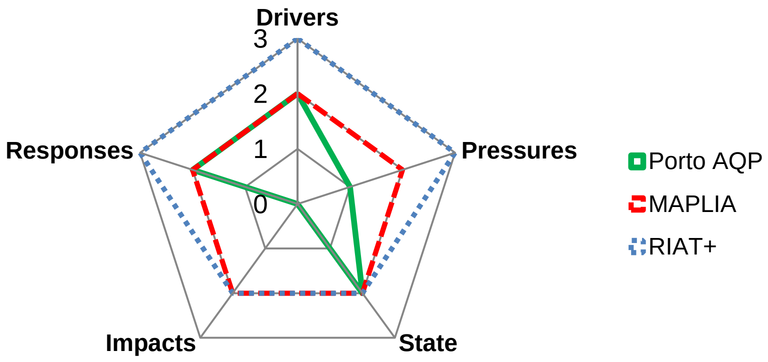


Figure 5.9 - Comparative radar chart for the original Northern Region air quality plans, the MAPLIA and the RIAT+ applications (3=high; 2=medium; 1=low; 0= not considered).

It is possible to observe that the degree of complexity attained by the RIAT+ application is higher comparatively with the other two applications. In terms of DRIVERS, the level is high in the case of RIAT+ and medium in the remaining cases because used high activity data detail (including fuels) and activity data representative of the particular study area, respectively.

Concerning PRESSURES, the low level in Porto AQP is explained by the reduced spatial disaggregation of the emissions, which were disaggregated by municipality and allocated to SNAP code level 1. In the case of MAPLIA, for some macrosectors a bottom up approach was used, even if the emissions were also allocated to SNAP code level 1 detail; thus the level of detail is medium. The maximum level of detail was achieved by RIAT+ due to the use of spatial proxies to disaggregate the emissions in order to achieve the SNAP code level 3 detail.

When we look to the STATE block we realize that the level of complexity is the same for all the applications. The maximum level is not attained because a single deterministic model was used instead of a “chain” of models from European to street level scale.

In the IMPACTS block, with the exception of Porto AQP, which does not include any kind of impacts evaluation, a medium level of detail was achieved in both MAPLIA and RIAT+ applications. The maximum was not achieved, because it involves a more detailed temporal and spatial description, as well as the consideration of activity patterns.

Lastly, in the RESPONSES block RIAT+ with its optimization approach achieved the maximum level of complexity, while the other two applications were based on scenario approach.

5.5 Discussion and future perspectives

The increasing number and complexity of IAM options to support environmental decisions, and the limited capacity of a single decision-maker to integrate and process all the information, emphasizes the need to develop methods aggregating the information in a consistent manner. The DPSIR framework through radar charts can help decision–makers and researchers to compare different IAM options. However, the choice of an IAM has to take into account the available data, the regional/local specificities and the financial resources.

Emissions can be considered the most uncertain input in the IAM chain. Emission inventories may have different levels of detail depending on the availability of data and their uncertainties. For both approaches, case scenario and optimization, it is important to have an inventory with the highest level of detail to correctly link the particular source of emission with the set of reduction measures.

There are different ways to characterize the air quality state. The approach used in both IAM cases is based on the application of a deterministic model that was validated over the study area. Using a deterministic model such as TAPM has the advantage of getting the spatio-temporal characterization of the study area and thus obtaining air quality concentration levels where no measurements (taken routinely or during a measurement campaign) are available. Usually the use of these models requires a simulation period that can vary from a couple of hours to a few weeks. In the case of the MAPLIA application every time a new emission scenario has to be evaluated it is required to run the air quality model again to assess the air quality state. It is impossible to compare a large number of scenarios and to help on time the decision-making processes. On the other hand the RIAT+ application makes use of surrogate models (Artificial Neural Networks (ANN)) to reproduce the link between precursor emissions and secondary pollutant concentrations. ANN mimic the behavior of determinist models, and after training, they can test different emission scenarios in a few seconds.

Even if is not directly mandatory by EU legislation the quantification of air pollution impacts on health it is a key element for the design of effective local and regional AQP. In both IAM study cases the population exposure was quantified. The health effects of pollutants include short term (acute) and long term (chronic) effects, and according with the Health Risks of Air Pollution In Europe (HRAPIE) project (WHO, 2013a) of the World Health Organization, the impacts of the different pollutants should not be added to avoid, in most practical circumstances, an overestimation of the true impact. Information about concentration–response functions specific for a country or region is difficult to find, and is rarely used. In the MAPLIA and RIAT+ applications, generic health functions (mortality and morbidity) taken from epidemiological studies were used.

The individual exposure, taking into consideration time-activity patterns and indoor and outdoor concentrations, is rarely considered in IAM applications or studies.

Sensitivity and uncertainty analysis are important issues for IAM results. However, due to the difficulty in applying methods to the overall system they are not widely used. Analytical and numerical sensitivity and uncertainty methods are usually applied to each DPSIR block, individually.

The optimization approach requires more detailed information in terms of emission inventory to link PRESURES to RESPONSES. Costs are very important because optimized results depend on the specific abatement costs provided. This type of approach can be useful when a large list of measures is available (usually just technical measures), and the goal is to find the best set to achieve established targets. Policies involving non-technical measures (e.g. behavioral and lifestyle changes) are more difficult to quantify in terms of their associated costs.

The other approach (scenario analysis) makes easier to introduce local measures, because it requires less information. It is difficult however, to test a large number of scenarios, because this implies running a CTM model per scenario. In the future, these kinds of systems should include surrogate models in order to reduce the time required to simulate a new scenario and better help in decision-making processes. In order to easily compare the different scenarios, a Multi-Criteria Decision Analysis (Achillas *et al.*, 2011) can be done, considering: social acceptance, applicability, investment costs, health effects, and environmental effects, among others.

In summary, the applied DPSIR framework can be used to easily compare IAM models or tools, and to better understand the required degree of complexity. It was possible to realize that Porto`s AQP were developed in a simple way. Regarding the tested IAM approaches, the degree of complexity is higher in RIAT+. However both IAM approaches have advantages and disadvantages and possibly a way forward would be to develop a mixed system easy to be applied by decision-makers and to consider their particular abatement measures based on surrogate models.

Simpler tools, to be applied at city level or to entire region, and with the capacity to provide support to decision-makers in the conception, design, implementation and assessment of air quality and low carbon policies, are a real need, and must be developed in close relationship with the end users.

6 An Integrated Assessment Modelling System to Support Decision-Making: Design and Implementation

Abstract

This paper describes the design and application of a modelling system capable of rapidly support decision-makers in their urban air quality strategies, in particular providing emission and concentration maps, as well as external costs (mortality and morbidity) due to air pollution, and total implementation costs of improvement measures. Results from a Chemical Transport Model are used to train Artificial Neural Networks and to link emission of pollutant precursors to urban air quality. A ranking of different emission scenarios is done based on Multi-Criteria Analysis, which includes in the decision process economic and social aspects. The Integrated Urban Air Pollution Assessment Model (IUAPAM) was applied to the Porto city (Portugal) and results reveal that is possible to reduce the number of premature deaths per year, attributable to particulate matter (PM10), from 1300 to 1240 (5%), with an investment of 0.64 M€/year, based on fireplaces replacement.

This chapter was published as:

Relvas H., & Miranda, A. I. (2018). An urban air quality modelling system to support decision-making: design and implementation. *Air Quality, Atmosphere & Health*, 1-10.

6.1 Introduction

Good air quality is still a challenge in the world and in Europe in particular. The last “Air quality in Europe” report, delivered by the European Environment Agency (EEA, 2016), indicates that air quality policies resulted, and continue to result, in many improvements. However, substantial challenges remain and considerable impacts on human health and on the environment persist (Costa *et al.*, 2014; Lelieveld *et al.*, 2015; Newby *et al.*, 2014).

A large proportion of European urban populations are still exposed to air pollution levels that exceed European standards and, especially, the World Health Organization (WHO) Air Quality Guidelines. Estimates of the health impacts attributable to exposure to air pollution show that PM2.5 (particulate matter with an aerodynamic equivalent diameter lesser than 2.5 micrometres) concentrations in 2013 were responsible for 467 000 premature deaths in the 28 European Union Member States (EEA, 2016). Moreover climate change is likely to increase air-pollution-related mortality, in all regions in the world (except Africa) in particular in India and East Asia (Dias *et al.*, 2012; Silva *et al.*, 2017).

Even if there are many possible interventions that can be made at the city scale through measures, such as investment in public transport, low emission zones (LEZ), changes on heating and cooling systems, street washing, it is difficult for policy-makers to quickly assess the consequences of policies and measures on local air quality and human health. The efficacy of those policies and measures often depends on a combination of specific factors, such as meteorology, pollutants chemical reaction and dispersion, or topography, among others.

Integrated assessment models (IAM) can contribute to the evaluation of strategies for environmental pollution control and improvement. Ideally, such models cover the whole range of the problem from emissions of pollutants to their environmental and health effects (Karvosenoja *et al.*, 2010; Vedrenne *et al.*, 2014). IAM models typically answer questions of the "what if…" type (scenario analysis); by defining different scenarios for human activities the models explore a variety of possible future developments, thus illustrating possible consequences of alternative strategies (Thunis *et al.*, 2016b). Some IAM also include options for optimization (Carnevale *et al.*, 2012a). In scenario analysis 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 (Miranda *et al.*, 2016b). The optimization approach requires more detailed information in terms of emission inventory, in order to link activities to measures. This type of approach can be useful when a large list of measures and related information is available (usually just technical measures) and the goal is to find the best set to achieve established targets. In this kind of approach source–receptor relationships are used to reproduce the air quality model behaviour (Carnevale *et al.*, 2012b), in order to increase the speed and allow performing thousands of optimization calculations. Both approaches have same advantages and disadvantages and a possible way forward would be to develop a mixed system to be easily applied by decision-makers.

The main objectives of this paper are: (i) to design an urban integrated assessment modelling system to rapidly support decision-making; (ii) to test the designed system in the Porto Urban Area; and (iii) to identify future research lines.

This Chapter is structured as follows: Section 2 introduces the Integrated Urban Air Pollution Assessment Model (IUAPAM). Section 3 tests the IUAPAM in the Porto Urban Area and provides a description of the dataset and the main results. Section 4 is dedicated to the analysis of the multi-criteria decision results, while Section 5 is devoted to the conclusions.

6.2 The IUAPAM approach overview

The Integrated Urban Air Pollution Assessment Model (IUAPAM) has been developed aiming at supporting regional and local authorities in the design and assessment of air quality improvement plans, or emission reduction strategies. The model is based on the relationships between emissions and concentration levels, and can be used to answer the following questions:

- How efficient is a given emission reduction strategy in terms of cost, air quality and health impacts?
- Is a given emission reduction strategy for the study area strong enough to achieve the air quality targets?
- How air quality measures belonging to an emission reduction strategy can be ranked?

These questions can be answered by a consistent approach using IUAPAM. The system provides estimates on the costs and air quality/human health benefits of alternative emission control strategies. Figure 6.1 displays the main IUAPAM components as well as the principal inputs and outputs.

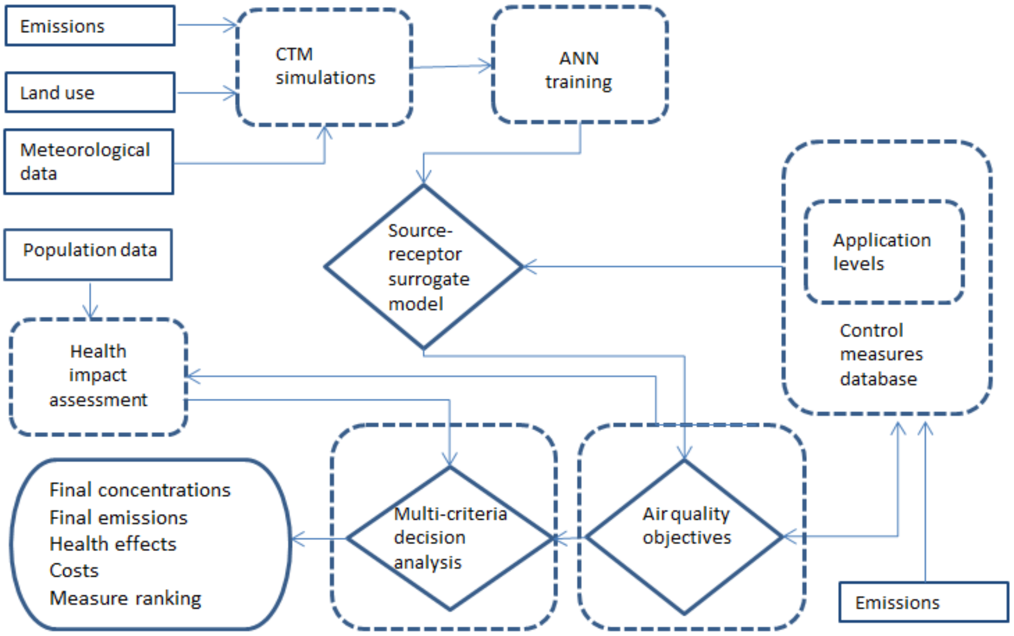


Figure 6.1 - Scheme of IUAPAM model.

First meteorological data, land use and emissions are used as inputs to a Chemical Transport Model (CTM); its results are then used to train and validate Artificial Neural Networks (ANN) and to establish source–receptor relationships. After that the user can select one air quality objective (e.g. annual mean PM10 concentration) and improvement measures from a database. IUAPAM will posteriorly estimate the new concentrations and perform health impact assessment. In the last stage Multi-Criteria Decision Analysis (MCDA) is used to compute a final measure ranked list taking in account different criteria.

The model was developed in Python programming language, and at the current stage it does not include an interface. It allows for a rapid exploration of potential air quality improvements resulting from regional/local emission reduction measures/scenarios.

IUAPAM provides an open environment prepared with visualization capabilities that allow creating maps with a high quality and interpretative value. To this respect, outputs can be obtained as indicator maps (visually) while data can be exported in tabular text files (.csv, .txt). In a near future, a graphical user interface (GUI) for facilitating input file preparation and output results display will be available aiming to minimize the involvement of the user with the code.

6.2.1 Emissions

IUPAM is preconfigured to work with a predefined set of emissions input data. By default, an emission inventory that covers the Portuguese main cities at high resolution (1 x 1 km^2) is included. Different emission inventories and spatial resolutions can be used; this allows for the simple and straightforward testing of new air quality policies/measures for any given domain, locally or not. If no regional/local inventory exists, the emission data can be based on European inventories, such as EMEP (Vestreng *et al.*, 2007) or TNO-MACC (Kuenen *et al.*, 2014).

6.2.2 Chemical transport model

Successful air quality policy and management require accurate and detailed information on ambient air quality levels in order to assess the state and detect any problems that may be relevant to health impacts, such as an exceedance of legislated limit values. In IUAPAM a Chemical Transport Model (CTM), the TAPM model (Hurley *et al.*, 2005), has been used to simulate 10 different emission scenarios, that are available in the system by default for the Portuguese simulation domain, namely for the main cities (Lisbon and Porto). The user, by means of a different CTM and/or spatial resolution, can perform different simulations in order to provide emission-concentration relationships to IUAPAM for a particular case study.

A comprehensive database of widely used and validated modelling tools is available at the EIONET Model Documentation System (URL2). In addition, detailed technical guidance on best modelling practices for assessment purposes can be found in the EEA technical report 2011/10 (EEA, 2011).

6.2.3 The objectives

The Air Quality objective can be defined by the user as one the following indexes:

- Annual mean PM10 concentration;
- Annual mean PM2.5 concentration;
- Annual mean NO_2 concentration.

The Air Quality Index (AQI) is a function of emissions. Since the user can impose different reductions to different emission macrosectors, the index can be described as follows:

$$\mathrm{AQI}\ (\mathrm{E}(\alpha)) = \beta\left(E_{x,y}^{z,k}\left(\alpha^{z,k)}\right)\right) \tag{1}$$

Where:

- β is described in this study by using source–receptor models.
- $\mathrm{E}_{\mathrm{x,y}}^{\mathrm{z,k}}$ is the emission of the z precursor species for macrosector k, for the cell x,y;
- k ϵ K= is the CORINAIR emission macrosector (Selected Nomenclature for Air Pollution - SNAP level 1) (1, 2…11) ;
- z ϵ Z = identifies the precursors (particulate matter (PM), nitrogen oxides (NO_X), volatile organic compounds (VOC), ammonia (NH_3), sulphur oxides ($SO_{X,}$));
- α= $\alpha^{z,k}$ is the decision variable set, namely the percentage of precursor z emission reduction in macrosector k;

The abatement costs associated to each macrosector k can be calculated as follows:

$$\mathrm{AC(m)} = \sum\nolimits_{\mathrm{m} \in \mathrm{M}} \mathrm{C_k X_{mk}} \qquad (2)$$

Where:

- AC are the abatement costs [euro] for macrosector k.
- m ∊ M= (1, 2…n) is the measure / technologies that can be applied in macrosector k to reduce pollutant z.
- C_k are the annualized unit costs [euro] of the application of measure/technology
- X_{mk} represents the application rate (between 0 and 1, respectively minimum and maximum value) of measure/technology m to macrosector k.

Therefore, the total costs [euro] are:

$$TC(m) = \sum\nolimits_k AC \qquad (3)$$

6.2.4 Artificial neural networks

In order to quickly compute different emission scenarios and reduce computational time, non-linear models based on Artificial Neural Networks (ANN) (e.g. Carnevale *et al.*, 2012b; Relvas *et al.*, 2017) may be applied. This approach compared to the traditional linear-source receptor relationships (Seibert & Frank, 2004; Vedrenne *et al.*, 2014) captures the non-linearity in the relationships between emissions and concentrations, maintaining a low Central Processing Unit (CPU) time.

To identify these ANN, it is first necessary to select the model type, architecture and an input shape adequate to the domain under study and, then, to identify a set of emission-concentration scenarios, that need to be simulated using a deterministic air quality model. To figure out the most suitable input shape it must be considered that the AQI values in a given cell may depend also on the precursor emissions of distant cells. A second key factor, to be considered, is the dominant wind directions. A technique already presented in literature (Carnevale *et al.*, 2012b) allows to consider both aspects by aggregating the emissions from cells belonging to four triangular slices, located around the cell for which the AQI has to be computed. However, other different techniques can be used (e.g. Clappier *et al.*, 2015).

By default, the IUPAM includes code to train ANN making use of a Python library called “Pyrenn”, which is capable to create a feed forward or recurrent neural network. The library allows saving the structure and the trained weights of a neural network to a .csv file. Other Python libraries can be used as other kind of software. A pre-processor is used inside IUPAM in order to provide ANN inputs. It considers input coming from four contiguous quadrants, thus considering prevalent wind directions. This configuration has the advantage of being adjustable to different conditions by modifying the dimensions of the quadrants.

The main steps related with the ANN process are described as follows:

1) Normalizing the input data,
2) Defining the input dataset,
3) Splitting the data into training/test set,
4) Defining functions, the number of layers and neurons,
5) Training and testing networks,
6) Analysing the network output data,
7) Returning the output data from the normalized mode,
8) Evaluating the performance of the neural network and eventual overfitting.(1)

(1) Overfitting occurs when the ANN has learned to replicate the training dataset but has poor fit with new datasets.

6.2.5 Health impact assessment

Air pollution is an important stimulus for the development and exacerbation of respiratory diseases, such as asthma, chronic obstructive pulmonary disease, and lung cancer, as well as a substantial impact on cardiovascular disease (Costa *et al.*, 2014; Lim *et al.*, 2012). The elderly and children are particularly vulnerable to the health impacts.

Based on the achieved air quality state for a specific abatement scenario, IUPAM can estimate the human health impacts related with PM and NO_2 making possible to do cost–benefit analyses. Generically the impacts can be computed as:

$$\Delta\mathrm{R} = \sum_{z=1}^{Z} CRF.IR.Pz.Cz \qquad (4)$$

Where:

- ΔR is the response as a function of the number of the unfavorable implications (cases, days or episodes) over all health indicators (i = 1, …, n);
- CRF is the correlation coefficient between the pollutant concentration variation and the probability of experiencing or avoiding a specific health indicator i (%, i.e. Relative Risk (RR) associated to a concentration change of 10 µg/m^3;
- IR is the baseline morbidity/mortality annual rate (%);
- Pz is the population exposed to pollution in cell z;
- Cz indicates the average pollutant concentration, in cell z.

The evaluation of the health cost linked to the health impacts can be performed by multiplying the ΔR value by its associated economic value.

The health outcomes were selected based on the availability of long-term CRF functions meta-analysed from peer-reviewed literature. We follow the methodology recommended for European health impact assessments by the Health Risks of Air Pollution In Europe (HRAPIE) project (WHO, 2013a) of the World Health Organization. The Relative risk (RR) data in Table 6.1 may be interpreted as follows: the RR of long-term mortality for a 10 µg/m^3 PM10 increment is 1.045 for people older than 30 years, consequently the number of premature losses increase by 4.5% for every 10 µg/m^3 PM10 increment.

Table 6.1 - Relative risk (RR) estimates, baseline data external costs used for the estimation of mortality and morbidity due to air pollution (per 10 µg/m^3 increase).

Pollutant	Health outcome	Age group	RR per 10µg/m^3 (95% CI)	Baseline annual rate (%)	Cost (€)	Unit	Sources
PM10	Chronic bronchitis (incidence)	>18 yr	1.117 (1.040-1.189)	3.9	11,300 (a)	year	(WHO, 2013a)
	Chronic bronchitis (prevalence)	6-18 yr	1.080 (0.980-1.190)	18.6	11,300 (a)	year	(WHO, 2013a)
	Total mortality	<1 yr	1.040 (1.020-1.070)	2.5	40,000	case	(Desaigues *et al.*, 2011; WHO, 2013a)
		>30 yr	1.045 (1.029-1.060)	1.0	40,000	case	(Castro *et al.*, 2017; Desaigues *et al.*, 2011; WHO, 2013a)
PM2.5	Total mortality	>30 yr	1.062, (1.040-1.083)	1.0	40,000	case	(Desaigues *et al.*, 2011; WHO, 2013a)
NO_2	Total mortality	>30 yr	1.055 (1.031-1.080)	1.0	40,000	case	(Desaigues *et al.*, 2011; WHO, 2013a)
	Prevalence of bronchitic symptoms in asthmatic children	5–14 yr	1.021 (0.99-1.06)	21.1	11,300	year	(WHO, 2013a)

(a) Based on average cost per day of hospitalization of 1982 €, and an average hospitalization time of 5.7 days/case.

Following the recommendation of the HRAPIE project, estimated impacts of the different pollutants are not added to avoid, in most practical circumstances, an overestimation of the true impact. Impacts estimated for one pollutant will, on the other hand, underestimate the true impact of the pollution mixture, if other pollutants also affect that same health outcome. Therefore, depending of the air quality objective selected by the user (e.g. annual mean PM10 concentration) the IUPAM will automatically selected the related health functions.

The user can select mortality, morbidity or both considering long-term effects. According to the WHO (2013a) cost–benefit analyses show that mortality impacts dominate the analysis as a whole and mortality data are complete and better standardized in EU countries.

6.2.6 Multi-criteria decision analysis

The IUAPAM combines the scenario approach, able to identify sound solutions when dealing with easily measurable or estimated indexes, like costs and pollutant concentrations, with a Multi-Criteria Decision Analysis (MCDA) that gives the opportunity to include social aspects and to create an air quality measures/scenarios ranking. MCDA methods have been extensively applied to a range of environmental management challenges (Kiker *et al.*, 2005).

MCDA methods can be broadly classified into value measurement models, outranking models, and reference-level models (Thokala & Duenas, 2012). Once we are interested in establishing a ranking of the different scenarios/measures, we opted by outranking models. Outranking methods typically involve making pairwise comparison of alternatives on each criterion, which, in turn, are then combined to obtain a measure of support for each alternative being judged the top-ranked alternative overall (Thokala *et al.*, 2016).

In this study, the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) (Kiker *et al.*, 2005) is used, but there are other options like the ELECTRE method family (Figueira *et al.*, 2013; Roy, 1990), or GAIA (Brans & Mareschal, 1994). A comprehensive review of PROMETHEE methodologies and applications is provided by Behzadian *et al.* (2010).

PROMETHEE is based on a pair-wise comparison of alternatives along each recognized criterion. Alternatives are evaluated according to different criteria (defined by experts or decision-makers), which have to be maximized or minimized. The implementation requires two additional kinds of information (Behzadian *et al.*, 2010):

- The weight - determination of the weights is an important step in all multi-criteria methods. The decision-maker needs to be able to weigh the criteria appropriately.
- The preference function - for each criterion, the preference function translates the difference between the evaluations obtained by two alternatives into a preference degree ranging from zero to one. In order to facilitate the selection of a specific preference function, six basic types are available (Brans & Vincke, 1985). For each criterion, the value of an indifference threshold, q; the value of a strict preference threshold, p; and the value of an intermediate value between p and q, s, has to be fixed.

In this work, the Visual PROMETHEE software (URL10), which has been developed to facilitate the PROMETHEE process, was used. Different MCDA software tools can be found in literature (Mustajoki & Marttunen, 2017).

6.3 Test application results

IUAPAM was applied to the Northern Region of Portugal to test emission reduction scenarios over the Porto Urban Area aiming to decrease PM10 levels in the air. This area is densely populated and industrialized and is repeatedly affected by high PM concentrations. The Porto Urban Area had in 2015 around 1 342 000 inhabitants and a mortality rate of 1050 deaths per 100,000 inhabitants (see Table 6.2).

Table 6.2 - Key figures of the Porto Urban Area (Source: National Statistical Institute of Portugal - INE).

Feature	Value
Number of municipalities	11
Area	1024 km^2
Population in 2015	1 341 432
Environmental public institution	Northern Portugal Regional Coordination and Development Commission (CCDR-N)
All-cause mortality rate in 2015	8800 deaths per 100,000 inhabitants
Life expectancy at birth in 2015	77.6 years for male, 83.3 for women

As dataset used for the identification of a surrogate model through ANN, the results of 10 yearly simulations carried out with hourly resolution using the TAPM model, and already described by Relvas *et al.* (2017) and Miranda *et al.* (2016b) have been considered. TAPM simulations have to be compulsorily limited in number due to the computational time needed by the deterministic TAPM model, but they must be able to represent, as closely as possible, the cause-effect relationship between PM10 precursor emissions (NOx, SO_2, PM10, and VOC) and the average yearly PM10 concentration. The emission data for year 2009 (provided by the Portuguese Environment Agency) was used to create the different emission scenarios, the domain has been divided into 5625 squared cells, each with a size of 2 × 2 km^2. Further details on emission scenarios creation can be found in Relvas *et al.* (2017).

6.3.1 Reference vs what-if scenarios

The transport sector (road traffic), together with residential combustion and industrial emissions, remain the main causes of air pollution in the Porto Urban Area. In order to test IUPAM four local emission reduction scenarios were generated:

- CLE - Current Legislation Level for the reference year (2020).

- S1 – taking in account previous published studies (Borrego *et al.*, 2010; Duque *et al.*, 2016) that identified residential combustion as an important contributor to the total PM10 emissions, this scenario implies the replacement/reconversion of 50% of the conventional residential fireplaces by more efficient equipment able to reduce 70% of PM10 emissions, according with the GAINS database (URL4).
- S2 - production processes are the major source of PM10 emissions in the Porto Urban Area (Relvas *et al.*, 2017). This scenario assumes the application of clean technologies (high efficiency de-dusters) in addition to good practice in industrial processes-storage and handling, which allows a reduction of 5% in PM10 emissions from production processes (SNAP 4).
- S3 - the use of diesel in transport has come under increasing scrutiny in recent years, as concerns about its impact on air quality have grown. We pretend to test the effect of baning diesel cars from Porto municipality. Taking in account the current Portuguese share of gasoline and diesel passenger vehicles (respectively 46.2 and 52.3%), considering the restriction applied to diesel vehicles older than 10 years (57%), and an motorization rate of 457 vehicles per 1000 inhabitants, a reduction of 32,000 diesel vehicles inside the municipality is expected. To estimate the resultant emission reduction, the COPERT4 emission model was used considering 1.4–2.0 cylinder diesel vehicles and EURO 4 standards (conservative estimate). An average of 20,000 km driven by vehicle by year was assumed. The total emission reduction is around 32 t/year of PM10 (exhaust and non-exhaust).

6.3.2 ANN training and validation

The default TAPM model simulations were used as dataset for the identification of the ANN. First, a pre-processor was used inside IUAPAM to provide ANN inputs. The ANN inputs (i.e. the sum of precursor emissions over the quadrants), were then pre-processed by means of a normalization procedure ([0, 1]), using the Python “Pyrenn package” and a backpropagation algorithm. Then the surrogate model was trained and validated. A log-sigmoid transfer function was used in the hidden layer, and a linear function was used in the output layer. Figure 6.2 shows the validation results for the PM10 neural network model, by means of a scatter plot that compares TAPM output results with the ANN outputs.

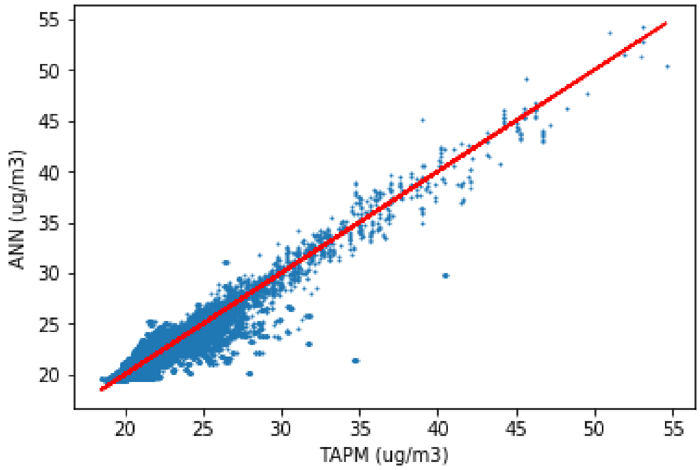


Figure 6.2 - Surrogate model validation scatter plot between TAPM (x-axis) and ANN (y-axis) for yearly PM10 [µg/m^3].

The value of correlation (R^2 = 0.95) and a low value of the normalized root mean squared error (RMSE = 0.62) highlight the good ANN performance, even if the identified neural networks slightly overestimate PM10. The obtained result is quite similar to the one achieved by Relvas *et al.* (2017) for the same set of ANN input data, using the Matlab Neural Network Toolbox as a tool.

6.3.3 Main results

After ANN training and validation of the four emission reductions scenarios were tested. Figure 6.3 displays the PM10 base case scenario concentrations (CLE 2020). Figure 6.4 shows the impact of the tree scenarios in relation to the base case (differences between the PM10 annually-averaged concentrations obtained for each scenario simulation and the base case simulation).

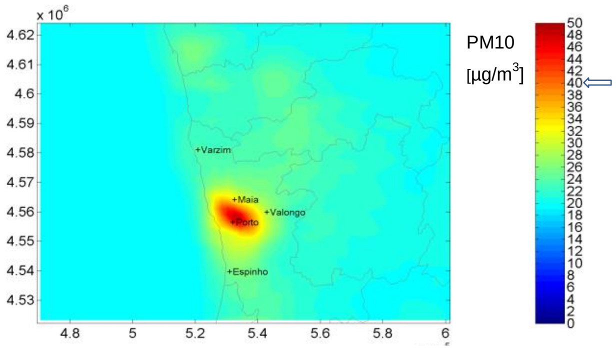


Figure 6.3 - Base case scenario (CLE 2020) PM10 concentration values annually-averaged. The coordinates (scale) are UTM (meters).

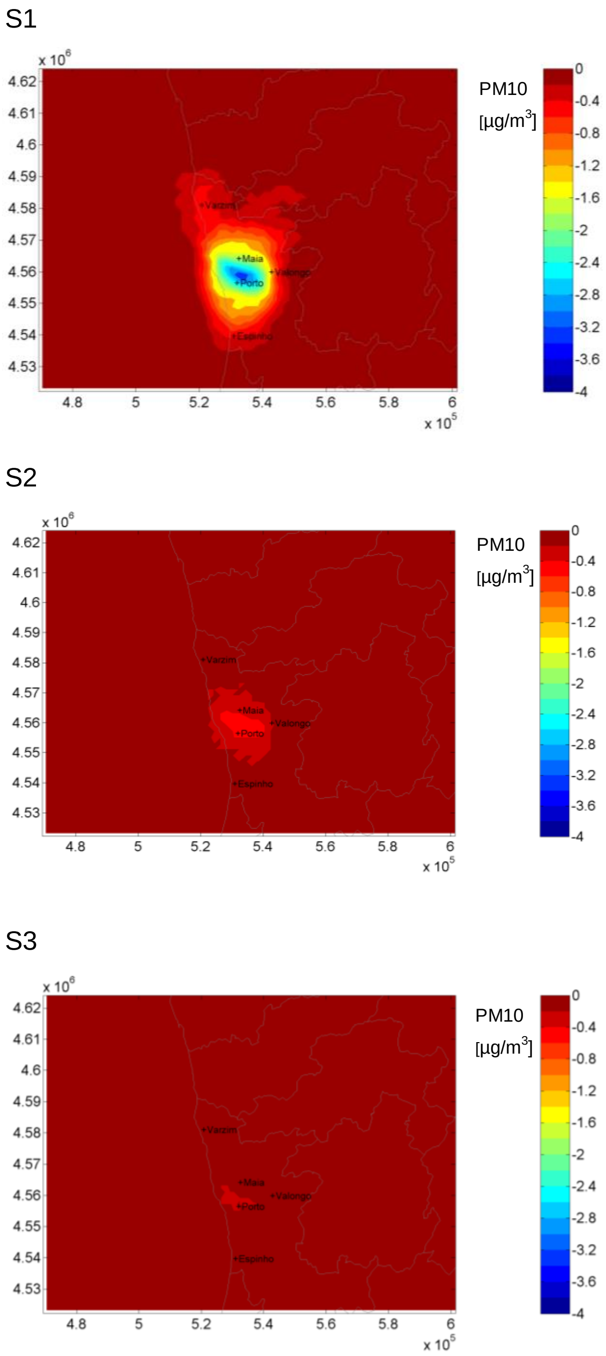


Figure 6.4 - Modelling results: reduction of PM10 concentrations comparatively to base case scenario CLE 2020. The coordinates (scale) are UTM (meters).

The results show that the Scenario 1 (fireplaces) is able to reduce PM10 levels up to 4 µg.m^{-3} over the Porto Urban Area, while the Scenario 2 and Scenario 3 only have a minor local benefit (Porto municipality). The restriction of circulation of old diesel vehicles (Scenario 2) allows reductions of up to 0.4 µg.m^{-3} on the annual mean of PM10, and the application of clean technologies in industry (Scenario 3) 0.6 µg.m^{-3}.

For all scenarios, despite the improvement of air quality, PM10 concentration values are still higher than the annual limit value ([PM10]>40 µg.m^{-3}) over the Porto and Gaia municipalities and the nearby areas. From the baseline concentration map (Figure 6.3) is possible to conclude that with the exception of the Porto and Gaia municipalities the remaining domain is characterized by moderately low PM10 annual mean concentrations (18-20 µg.m^{-3}).

The Figure 6.5 shows the IUAPAM estimate for total mortality (population <1 and >30 years old) due to exposure to PM10 for all the scenarios in analysis. Our results suggest that with the CLE2020 scenario the premature mortality attributable to PM10 can reach 1300 deaths per year, just in the Porto Urban Area (11 municipalities).

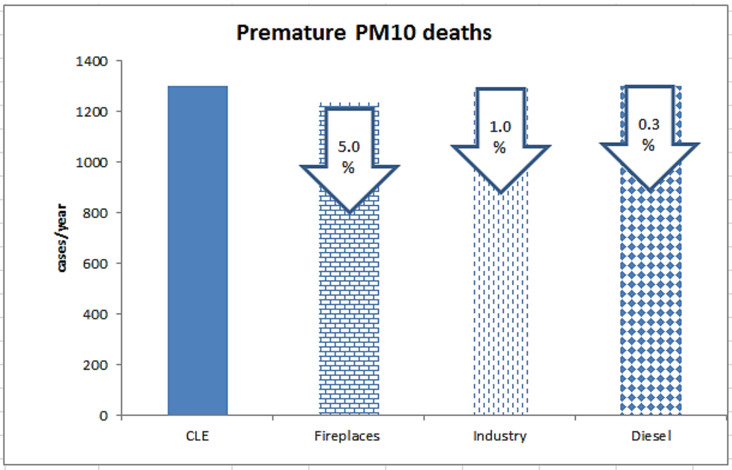


Figure 6.5 - IUAPAM estimate for total mortality (population <1 and >30 years old) due to exposure to PM10 for the 4 simulated scenarios.

Among the three tested scenarios the Fireplaces is the one able to reduce more the number of premature deaths (less 65 premature deaths). Nevertheless, the Industry and Diesel scenarios should also be considered in air pollution control strategies, because they can reduce 12 and 4 premature deaths per year, respectively.

Notwithstanding the improvement in air quality and health, stronger air quality control measures will be needed, particularly in the Porto municipality, in order to reduce the number of premature deaths.

6.4 Multi-criteria analysis of scenarios

Table 6.3 displays the list of tested air quality scenarios and related outputs: the internal costs (associated to measure implementation), the final Porto Urban Area average PM10 concentration, and the external (or estimated health benefits) costs based on IUPAM health functions.

Table 6.3 - List of air quality scenarios and related outputs.

SNAP Macrosector	Code	Measure	Application rate (%)	Internal costs (M€/year)	Average PM10 Concentration (µg/m^3)	Health (M€/year)
2	S1	Fireplace	100	0.64	26.50	2.59
4	S2	Industry	100	3.50	27.21	0.48
7	S3	Diesel	100	1.03	27.35	0.14

The S1 scenario requires the replacement of 14,122 units of open fireplaces by new improved fireplaces, with an average estimated cost of 900 €/unit and a lifetime of 20 years.

The S2 scenario involves good practice in industrial processes-storage and handling, which is difficult to quantify in terms of costs, and dusters (e.g. cyclones and electrostatic precipitators), which price depends of the removal efficiency and industrial dimension. We considered a public found of 3.5 M€/year available to industrial emission improvements.

The S3 scenario demands the installation of new signage (17.3 k€·km^{-2} and a lifetime of 25 years) and the operationalization of surveillance (24.6 k€·km^{-2}·y^{-1}); the costs are based on the Lisbon Low-Emission Zone (LEZ) (CCDR-LVT, 2006).

It is evident that in average the S1 scenario allows to reduce more efficiently PM10 concentrations, the difference is almost 1 µg.m^{-3} comparatively with S3. The PROMETHEE method was then employed considering three criteria:

- C1: social acceptance;
- C2: health benefit;
- C3: cost of the measures.

The qualitative criteria (social acceptance) have scores that range from 0 to 10 and the direction of preference is ascending. This means that if the scenario is easily accepted by the population, it has the maximum score of 10. Social acceptance is quite important because even if an air quality improvement measure is able to achieve good results it could be hard to implement, from a decision maker perspective, if it is not accepted by the population. Quantitative criteria (internal costs and health benefits) do not need to be normalized (see Table 6.4). Both qualitative scores and weighting factors for the criteria were defined by academic experts based on a questionnaire. It is assumed that both criteria cost and health benefit have a linear partial value function, but higher performance in criterion “health benefit” is better whereas lower performance in criterion cost is better. Table 6.4 shows the obtained scores for each scenarios and the weight of the different criterion.

Table 6.4 - Matrix containing the scores for each scenario, and the weight of the different criterion.

Code	Social acceptance	Cost	Health benefit
S1	5.0	0.64	2.59
S2	9.0	3.50	0.48
S3	6.5	1.03	0.14
Weight of the criterion	0.1	0.3	0.6

Table 6.5 presents the ranking of the different scenarios based on the different criteria and related weight. The ranking is based on the computation of two preference flows (Phi+ and Phi-). The positive flow expresses how much an alternative is dominating the other ones, and the negative flow how much it is dominated by the other ones. Phi net flow represents the difference between Phi+ and Phi-.

Table 6.5 - PROMETHEE ranking of the different scenarios and related Phi, Phi+ and Phi- scores.

Rank	Scenario	Phi (net flow)	Phi+	Phi-
1	S1	0.6466	0.7643	0.1177
2	S3	-0.1305	0.3177	0.4483
3	S2	-0.5160	0.1552	0.6712

The S1 is clearly the best choice, with the reduction of residential combustion emissions dominating the other proposed measures. The S2 is the worst one, taking in to account the three predefined criteria. The use of Visual PROMETHEE software in conjunction with IUAPAM is particularly useful when the number of scenarios/measures is ample, or when the number of criteria to satisfy is large; in this case different types of graphs/diagrams can be produced, in order to facilitate the analysis and support the decision making process.

6.5 Conclusions

Air quality policy-makers have to develop plans and strategies to reduce population exposure to air pollution. The IUAPAM is an IAM intended to comprehensively evaluate the effect of local and regional policies in the urban air quality and human health and to support the decision-making process.

IUAPAM makes use of ANN (non-linear models), going beyond the classical approach of using linear models, or computational demanding CTM, which facilitates the test of several emission scenarios. After training and validating the ANN, IUAPAM is able to give, in less than 30 seconds, emission and concentration maps, external costs (mortality and morbidity) due to air pollution, and the total implementation costs. The ranking of the different emission scenarios can also be done based on MCDA, allowing including in the decision process health, economic and social aspects.

The second stage of the work has been focused on the application of IUAPAM to the Porto Urban Area of Portugal to evaluate the impact of different emission scenarios on concentrations and population health due to PM10 exposure.

The results underline that to reduce particulate matter exposure in Northern Portugal, and more concretely in the Porto Urban Area, the Fireplaces scenario (S1) is the most relevant, allowing to reduce up to 4 $ug.m^{-3}$ PM10 annually-averaged concentrations, and to decrease 65 premature deaths per year. The other two scenarios appear to be more limited in their reach.

The scenarios have been considered for the application of a MCDA approach in order to compute a final scenario ranking aggregating social acceptance (evaluated by experts), as well as costs (external and internal). The final ranking made evident that S1 is clearly the best choice, and the industrial clean technologies (S2) is the worst one. The MCDA approach is however heavily dependent on the selection of the criteria to be considered and the experts’ choice of criteria weights.

In this work it was shown that IUAPAM is able to rapidly reproduce the effects of emission reduction scenarios, identifying the most suitable set of abatement measures, facilitating the decision-making process.

7 Conclusions and Future Developments

In 2016, 1.7 billion people (23 % of the world's population) lived in a city with at least 1 million inhabitants. By 2030 27 % of people worldwide will be concentrated in cities with at least 1 million inhabitants (UN, 2016). Without strong technological and behavioural changes, this will led to an increase of emissions in urban areas. In Europe successful control and regulation (e.g EURO emission standards, improvement in fuel quality) led to a general improvement of air quality during the last decades. However road traffic and the presence of industrial areas at the periphery of cities clearly impacts large portion of urban populations.

This Ph.D. thesis complements previous studies of the Research Group on Emissions, Modelling and Climate Change (GEMAC) concerning air quality modelling and exposure and health effects of air pollution.

7.1 General conclusions

The present Ph.D thesis has applied Integrated Assessment Models (IAM) to assess air quality impacts in urban areas. This Ph.D thesis has proved the capability of IAM to evaluate strategies for air quality improvement in urban areas. IAM cover the whole chain of processes from emissions of pollutants to their environmental and health impacts, including costs and benefits. Air quality modelling is an important part of the development of air quality strategies.

The second chapter of the thesis analysed the impact of different strategies to reduce urban air pollution in the Porto Urban Area. Four different scenarios were tested using the "The Air Pollution Model" (TAPM):

i. Scenario 1: Replacement of 10% of vehicles below the EURO3 class (diesel and gasoline) by hybrid model vehicles;
ii. Scenario 2: Introduction of a Low Emission Zone (LEZ) on a specific polluted area of Porto city, with the restriction for vehicles below EURO3;
iii. Scenario 3: Replacement/reconversion of 50% of the conventional fireplaces by more efficient equipment (residential combustion);
iv. Scenario 4: Application of clean technologies that allow a reduction of 10% in PM10 emissions from production processes and industrial combustion.

These scenarios were compared to a base scenario (year 2012), in order to estimate the impact on PM10 and NO_2 concentrations. Emission and air quality results showed that:

i. PM10 daily concentrations are observed at night, reaching maximum values during the winter period, which can be related to residential combustion activities; the daily profiles of NO_2 follow the traffic diurnal cycle, with peaks in the morning and late afternoon.
ii. Traffic related scenarios (1 and 2) are the only ones that have impact on NO_2 concentrations. Scenario 1 results in a reduction of NO_2 levels of up to 4.5% over all the domain, while Scenario 2 only has a local benefit with a local reduction of the annual concentration of NO_2 reaching 3%. PM10 reductions are just marginally observed for Scenario 1.
iii. The residential combustion scenario allows PM10 reductions of up to 1.5% and the industrial scenario up to 3.5%.
iv. If all measures are considered a total reduction of 4.5% for both pollutants, mainly over the area of Porto for PM10 and extended across the overall domain regarding NO_2, is expected.
v. The comparison with observed values indicates that TAPM over-predicts PM10 concentrations in the urban area and under-predicts $NO_{2.}$
vi. The application of all measures does not guarantee the accomplishment of PM10 daily limit value.

The presented scenario approach does not provide additional useful information from decision-making point of view, such as related health benefits, and an estimation of the implementation costs of the different measures.

The 3rd chapter of this thesis applies an integrated assessment tool to determine suitable abatement measures and to better support air quality decision-making for the urban areas of Porto and Brussels.

The RIAT+ system was tested for two European cases: the Brussels Capital Region (Belgium) and the Porto Urban Area (Portugal), in scenario analysis and optimization mode, respectively. RIAT+ is an integrated assessment tool that was designed to help regional decision-makers to select optimal air pollution reduction policies that will improve the air quality at minimal costs. The study concluded that:

i. In the Brussels case a lot of time was put into estimating precise measures while the impact on air quality of these measures is rather limited due to the dimension of the area selected. Even in scenario mode RIAT+ seems to be complex to apply and with limited added value in such case. The yearly average NO_2 concentration can decrease about 3 $\mu g/m^3$ when all traffic and all non-industrial heating measures are applied.
ii. In the Porto case a list of available technologies from an existing database was used and the main sectors were selected and identified. Nevertheless a more local list of measures

needs to be decided and discussed with stakeholders and policy-makers. With the optimization approach it was possible to have a first idea of the optimal investment costs and benefits to achieve a given PM10 air quality objective. The yearly average PM10 concentration can decrease about 1.3 µg/m^3 adopting emission reduction technologies costing around 35 Million Euros per year. The external costs are always higher than the internal costs.

iii. The applications confirm that this kind of tools can be practically applied in an integrated assessment of air quality.

iv. The biggest task when implementing such a comprehensive IAM is to obtain high quality input data *i.e.* information on local emissions and the cost and effectiveness of possible abatement measures.

v. If an IAM system uses artificial neural networks to relate emission changes to concentration changes, such relationships should be carefully tested and validated.

vi. Air quality measures may affect more than one pollutant at same time, subsequently optimization considering multi-pollutant should be tested.

The 4th chapter of this thesis analyses the effect of simultaneously reducing NO_2 and PM10 using RIAT+; local measures were also considered.

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 was 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. Local measures in addition to the technological measures dataset compiled by IIASA to Portugal were considered.

The emission and air quality results showed that:

i. RIAT+ is 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.

ii. Reductions of both PM10 and NO_2 concentrations will be achieved mainly through actions on traffic and domestic sectors.

iii. 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 relevant air quality improvement. However, these local measures could more easily be applied because are not dependent of specific legislation or national budget.

iv. 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.
v. However in same 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.

The 5th chapter of this thesis applies the DPSIR framework to air quality assessment analyses.

The different DPSIR blocks can be studied and classified according to the used degree of detail; this allows comparing different IAM approaches.

First the Porto Air Quality Plans (AQP) were analyzed within the DPSIR framework, then two different IAM applications over Porto (scenario analysis and optimization) were compared using radar charts.

The results showed that:

i. The used DPSIR framework can help researchers and policy-makers to compare different IAM options, in order to achieve the objective of air quality improvement.
ii. The AQP for Porto approached the DPSIR blocks in a low to medium level of complexity.
iii. The level of complexity is the same in both IAM applications for STATE and IMPACTS blocks. However RIAT+ application involves greater detail in DRIVERS, PRESSURES and RESPONSES.
iv. Both MAPLIA an RIAT+ approaches have same advantages and disadvantages and possibly a way forward would be to develop a mixed system easy to be applied by decision-makers and to consider their particular abatement measures based on surrogate models.
v. In both IAM approaches social acceptance of the measures was not considered.

The 6th chapter and last part of the thesis presents the IUAPAM and shows how it can be used to determine suitable abatement measures and to support decision-making.

The IUAPAM (Integrated Urban Air Pollution Assessment Model) allows for a rapid exploration of potential air quality improvements resulting from national/regional/local emission reduction measures. The model has been developed with the aim of supporting national, regional and local authorities in the design and assessment of their air quality plans, or emission reduction strategy.

The main IUAPAM features can be mentioned:

i. In order to quickly compute different emission scenarios, non-linear models based on Artificial Neural Networks (ANN) are used.
ii. A pre-processor is included in the system in order to facilitate the train and validation of ANN.
iii. Annual mean PM10, PM2.5 and NO_2 concentration can be provided by the model.
iv. Different air quality models and different spatial resolutions can be used.
v. Different emission reduction scenarios or measures can be added and tested.
vi. Health impacts (mortality and morbidity) are considered.
vii. Multi-criteria analysis allows considering different criteria and creates a final ranking of the measures/scenarios.

The test over the Porto Urban Area revealed that IUAPAM is able to provide emission maps and air quality maps, to estimate heath impacts, and to identify the most suitable set of abatement measures based on several criteria, including social aspects, facilitating the decision making process.

Despite the current availability of IAM tools, action on air quality at local level requires leadership, knowledge and resources to invest. It also requires much stronger and regular dialogue between local and national authorities, and integrated approaches combining different policy areas.

7.2 Future developments

Modelling is an essential tool for air quality management because it is not possible to measure continuously concentrations in all places. Often, AQP are focussed on urban areas where emission sources, as well as exposed population are concentrated. The development of consistent IAM tools for air quality management at urban scales is a very challenging task due to the complex factors that need to be considered (human health, social aspects, economic cost, etc.).

The IUAPAM system has proved to be a suitable tool for air quality management in urban areas. Within the modelling system, the availability of consistent emissions data as well as trained ANN is crucial.

In order to facilitate routine applications of IUAPAM a user-friendly interface should be developed based on a near contact with decision-makers and end users. This development needs to be carefully done because even a minor problem in the interface could effectively render the whole product unusable for a stakeholder.

In future, it should also be possible to select SOMO35 (the Sum of Ozone Means Over 35 ppb), normally used as an indicator of O_3 impacts on human health. This option is particularly useful if the tool is applied at regional scale.

Climate change is of fundamental importance nowadays given the expected increase of extreme weather events. The design and implementation of countermeasures in densely populated urban areas are an important goal in adaptation of societies to climate change in coming decades. In this sense, IAM systems should also be able to address synergies and trade-offs between policies to improve air quality and to reduce greenhouse gas (GHG) emissions.

Future collaborations with local authorities would allow defining specific air quality management plans in order to improve air quality in urban areas. In this thesis different emission scenarios have been addressed using IUAPAM. Furthermore, additional scenarios can now be planned and assessed:

- Impact of an increase of electric vehicles in urban air pollution,
- Impact of an increase of cycle lanes in city centre,
- Impact of metro lines expansion.

Finally, I believe that the developed work also demonstrates the potential of algorithms being used now, and of Artificial Intelligence algorithms in general, to support decision-making process, comparatively with current time demanding modelling approaches.

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Appendices

Appendix A – Total gridded emissions (PM2.5, SO_2, NH_3, VOC) for the CLE 2020 and MFR 2020.

Appendix B – ANN input and output values considering each quadrant.

Appendix C – ANN features considered to PM10 and NO_2 training and validation.

Appendix D – Fleet of taxis in Porto Urban Area municipalities.

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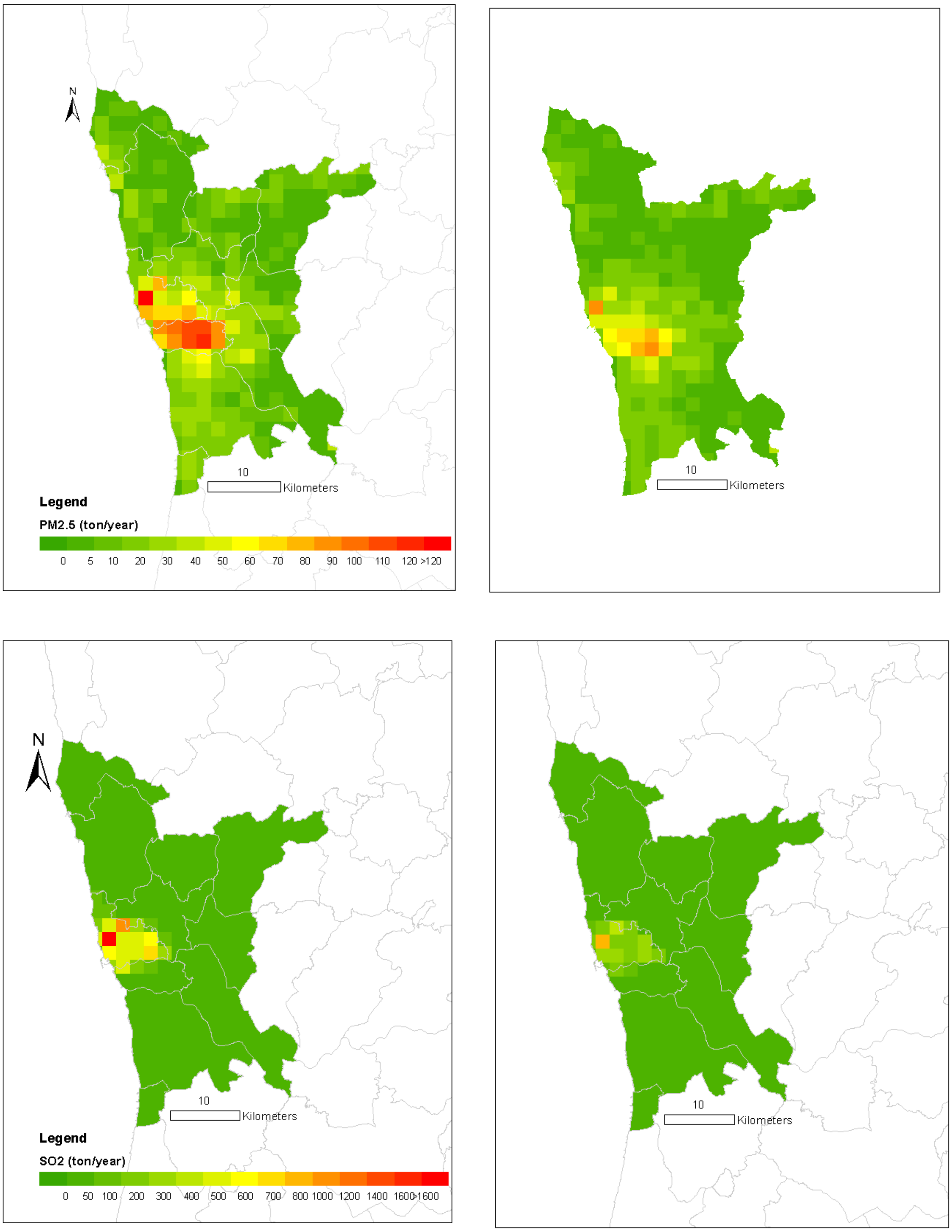
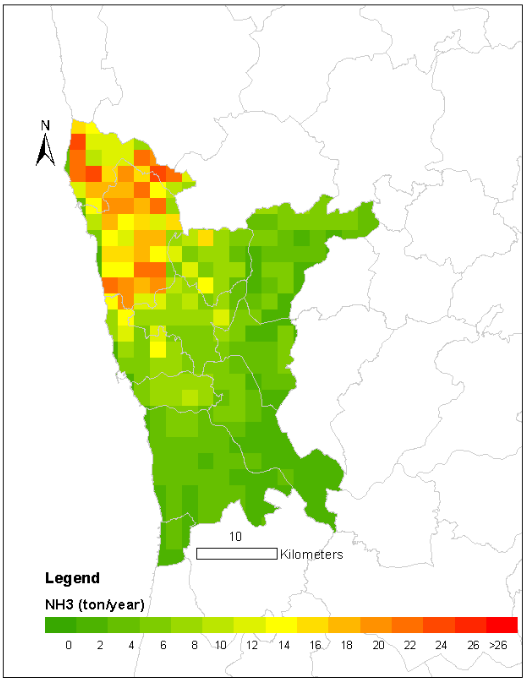
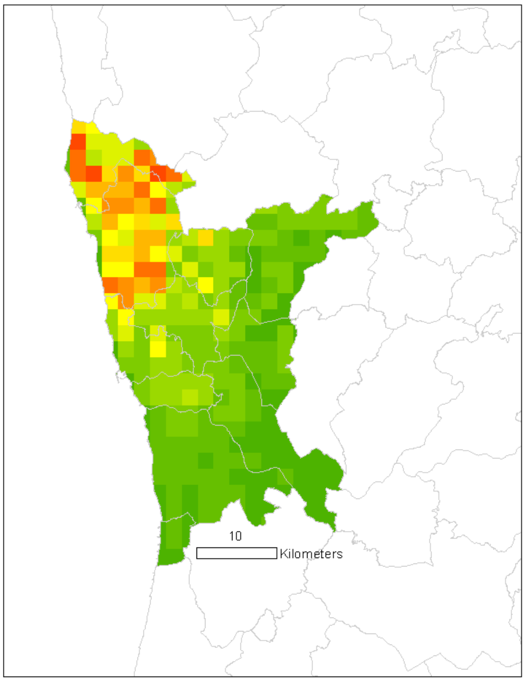
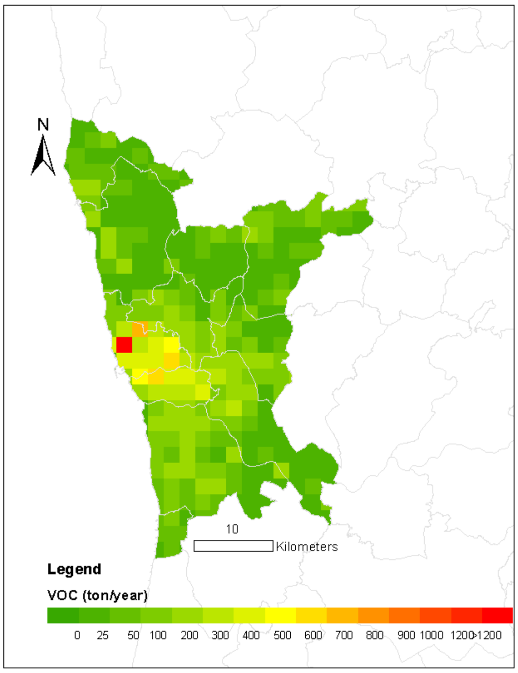
Appendix A

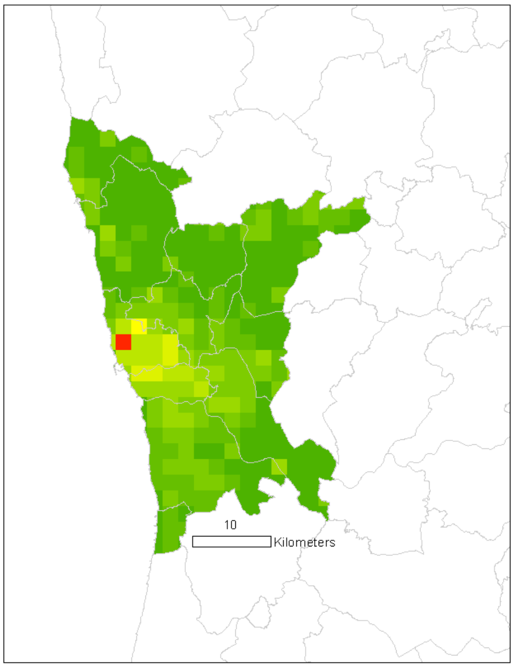
Total gridded emissions (PM2.5, SO_2, NH_3, VOC) at 2 × 2 km^2 resolution for the CLE 2020 (left) and MFR 2020 (right).




N
10
Kilometers
Legend
NH3 (ton/year)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
>26


10
Kilometers


N
10
Kilometers
Legend
VOC (ton/year)
0
25
50
100
200
300
400
500
600
700
800
900
1000
1200
>1200


10
Kilometers

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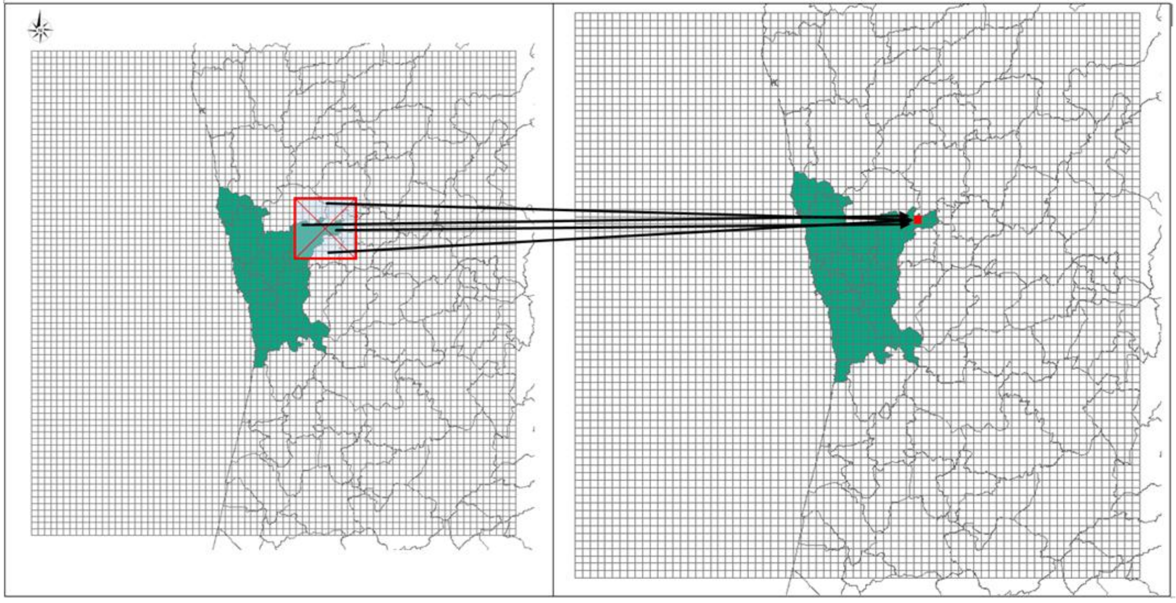
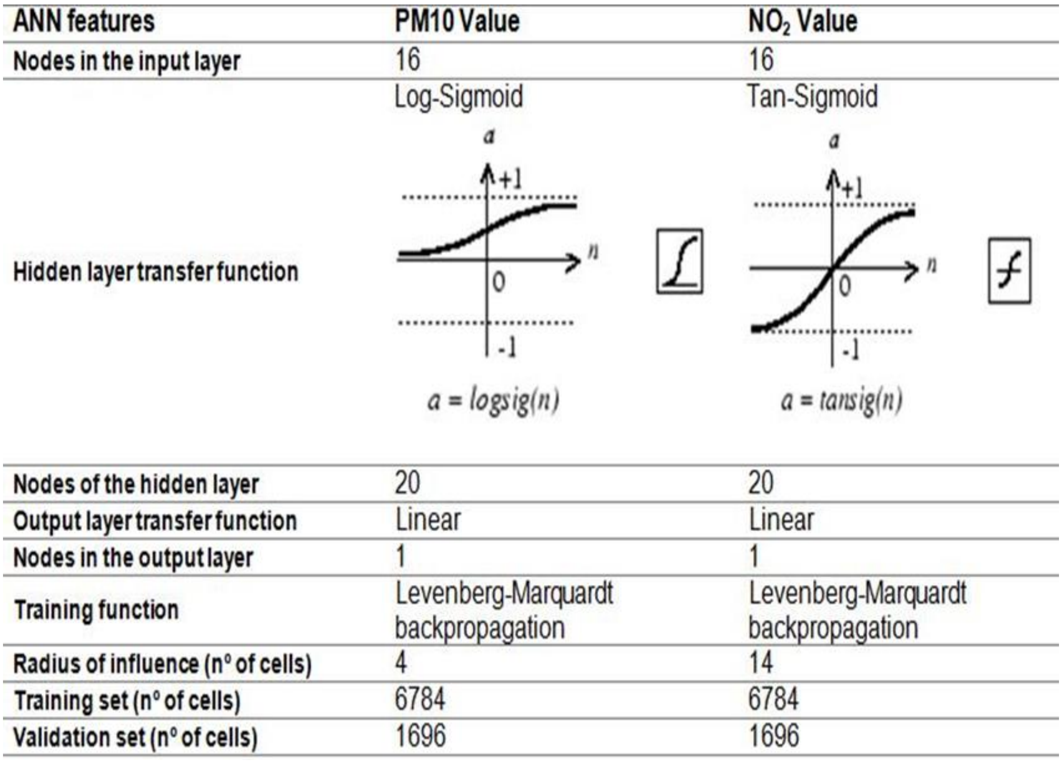
Appendix B

ANN input and output values considering each quadrant.



Appendix C

ANN features considered to PM10 and NO_2 training and validation.



ANN features	PM10 Value	NO_2 Value
Nodes in the input layer	16	16
Hidden layer transfer function	Log-Sigmoid $a = logsig(n)$	Tan-Sigmoid $a = tansig(n)$
Nodes of the hidden layer	20	20
Output layer transfer function	Linear	Linear
Nodes in the output layer	1	1
Training function	Levenberg-Marquardt backpropagation	Levenberg-Marquardt backpropagation
Radius of influence (n° of cells)	4	14
Training set (n° of cells)	6784	6784
Validation set (n° of cells)	1696	1696

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Appendix D

Fleet of taxis in Porto Urban Area municipalities.

Municipality	***Number of taxis***
Espinho	62
Gondomar	149
Maia	191
Matosinhos	235
Porto	1.775
Póvoa do Varzim	92
Santo Tirso	146
Trofa	43
Valongo	100
Vila do Conde	116
V.N. de Gaia	308

Source: Instituto da Mobilidade e dos Transportes (IMT, I.P.)