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Critical Literature Review

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Current air quality plans in Europe designed to support air quality management policies

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ABSTRACT

The intensification of the human activity in urban areas as a result of the increasing population has contributed to the air pollution worsening in cities. To reverse this trend, the European Commission established a legal framework to improve the air quality. Thereby the Member States need to develop air quality plans (AQP) for zones and agglomerations where air quality limit values are exceeded, in order to implement pollution control strategies and meet the legal requirements. Understanding the reasons for the levels of air quality non–compliance as well as evaluating available and commonly used tools to predict the air quality and their effects, is crucial for the decision–making process on air quality management policies. Based on a compilation of regional and local AQP, a review of assessment capabilities and used modeling tools to evaluate the effects of emission abatement measures on the air quality and health was performed. In most cases, models are applied to estimate emissions and to assess the resulting air quality from both reference and emission abatement scenarios. Air quality´s impacts on the health and environment are rarely quantified. Regarding the air quality assessment, beyond the modeling, monitored data for validation of simulations are also used. Some studies, however, do not include the use of air quality models, considering the monitoring network as spatially representative of the study domain (e.g. Lisbon Region, Riga, Malta). In order to overcome methodological limitations for quantifying the impacts of emission abatement measures, economic evaluation techniques or even Integrated Assessment Methodologies (IAM) have been developed. IAM, already applied in some AQP or case studies, namely for Antwerp and London, are used for assessing how reductions in emissions contribute to improve air quality, reduce exposure and protect human health.

Keywords: *Air quality plans, urban air quality, European legislation, modeling tools, integrated assessment methodologies*

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1. Introduction

Nowadays, poor air quality is recognized as one of the most pressing problems in urban areas with very harmful impacts on the health and environment (EEA, 2013). Moreover, the World Health Organization has recently classified air pollution as carcinogenic to human beings (WHO, 2013). According to the latest report on air quality in Europe (EEA, 2013), air pollution implications are mainly due to high levels of particulate matter (PM) and ozone (O_3) in the atmosphere. Anthropogenic emissions are identified as the greatest contributors to the concentration levels of air pollutants, but atmospheric phenomena occurring at different spatial scales also contribute to the increase of environmental damages.

In order to reduce air pollution effects, particularly in cities where the majority of the European population lives, it is important to define effective planning strategies for air quality improvement. For this purpose, Air Quality Plans (AQP) establishing emission abatement measures, previously known as Plans and Programs, have to be designed and implemented by the Member States (MS) of the European Union (EU) in accordance to the Framework Directive 96/62/EC on ambient air quality assessment and management. In 2008, based on the Framework Directive and in other previously existing legal documents, a new Air Quality Directive (AQD) (EC, 2008) was published, introducing new concepts, and simplified and reorganized guidelines. The application of numerical models is highlighted in this new Directive as a fundamental tool to better assess and manage air quality, encouraging their use in the preparation of AQP. These models must be used in combination with monitoring in a range of applications, since observed values are crucial for validation of these modeling approaches.

In most European MS the modeling tools used in AQP consider processes directly influencing the air quality, from the emission to dispersion and deposition of air pollutants, but do not include, for example, exposure or indicators related to health. Methodologies combining the effects of several emission abatement measures on the air quality and potential impacts on human health, as well as the economic evaluation associated to the implementation of measures and resulting external costs, enable cost–benefit/ effectiveness analyses of the control options (Amann et al., 2011) and are an added value to the decision–making process. For this reason, in the recent years, Integrated Assessment Methodologies (IAM) have been receiving prominence in the scientific literature (e.g. D'Elia et al., 2009; Carnevale et al., 2012). Nevertheless, the multi–scale and multi–pollutant analysis of the measures effect is seen as one of the most research challenges in order to decrease the uncertainties associated with the modeling.

The main objective of this study is to present a comprehensive literature review of existing assessment capabilities and modeling tools used by MS to evaluate the effects of local and regional AQP on the reduction of atmospheric pollutant concentrations and on human health. Limitations of the currently available assessment methods as well as the identification of best–practices for quantifying the overall impact of the measures are also addressed.

This review is mainly based on the analysis of AQP developed by MS, but there are two main initiatives/publications that have to be specifically mentioned: the assessment report on plans and programs reported under the Directive 1996/62/EC (Nagl et al., 2007), which is mainly focused on the emission abatement measures adopted by the Member States; and the FP7 project APPRAISAL (Air Pollution Policies foR Assessment of Integrated Strategies At regional and Local scales).

The paper is organized in the following sections: (a) overall structure of an AQP; (b) characterization of the reviewed AQP in terms of addressed air pollutants and used methodologies for assessing air quality and their effects taking into account the proposed emission abatement measures; (c) identification of the current methodological limitations and best–practices for quantifying the overall impact of the measures.

2. Overall Structure of an Air Quality Plan

The formulation and implementation of an AQP for improving air quality in polluted areas (e.g. zones or agglomerations), where air quality limit values are exceeded, should imply the characterization of emission sources, the assessment of the contribution of these sources to the ambient concentration levels, and the prioritizing of the sources that need to be tackled. According to the Directive 2008/50/EC (EC, 2008), zone is defined as a part of the territory of a MS, delimited by that MS for the purposes of air quality assessment and management. Agglomeration corresponds to a zone that exceeds 250 000 inhabitants, or with a given population density per km^2 to be established by the MS.

The integrated assessment of the various improvement options, namely emission abatement measures, in relation to their economic and technical feasibility and to their effects on the environment and human health should also be properly considered. Moreover, it is important to ensure that the air quality standards are achieved within the specified time frame in the AQP. Figure 1 illustrates the different components that have to be included in an AQP. Note that contributions from natural sources are not considered as an exceedance, as established in the Directive 2008/50/EC (EC, 2008).

To identify the emitting sources as well as to assess their individual contribution to the air pollutants concentration, source apportionment techniques are often conducted. This implies a previous knowledge of the atmospheric concentrations, measured or modeled at the receptor. The adoption of these techniques also allows understanding the maximum feasible air quality improvement that can be achieved by reducing emissions from those sources, due to the application of emission reduction policies for protection of the human health and environment (Air4EU, 2006; Borge et al., 2014).

Atmospheric emission inventories (AEI) must be as detailed and specific as possible, aiming to contribute to a more correct characterization of the reference situation. Accordingly, at the urban scale, bottom–up approaches should preferably be used instead of top–down emission inventories. However due to data compilation difficulties, it is a current practice to use disaggregation methods from a more comprehensive emissions inventory.

Meteorological conditions and chemical boundary conditions are also important components to consider in air quality modeling. A comprehensive set of meteorological conditions should be selected, since the meteorology influences the dispersion and the chemistry of the atmospheric pollutants and contributes to variations in polluted air arriving to a region from other regions and/or countries.

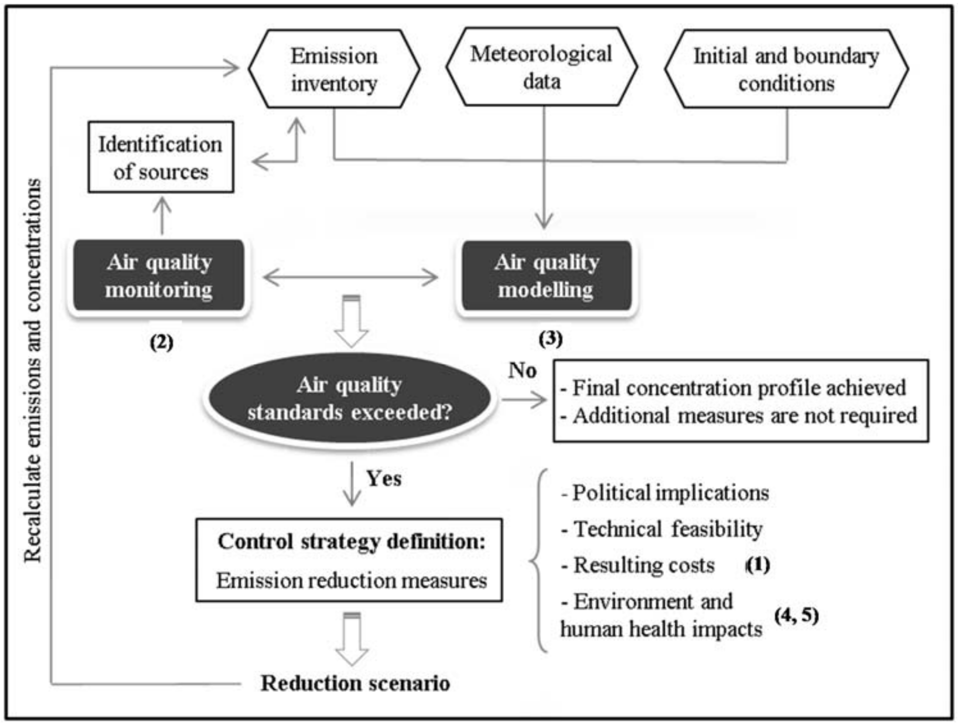

Figure 1. *Simplified scheme of the different stages to be included in an AQP. The components numbered in Figure 1 are related to the distinct aspects covered by the reviewed AQP, as referred in Table 1.*

The air quality (AQ) modeling results obtained taking into account the reduction measures contemplated in the reference scenario, should be compared with the EU air quality limit values. Additional measures oriented towards key activity sectors will be needed in case of non–fulfillment (Borrego et al., 2012), articulating them with the measures previously defined.

The applied methodologies should be consistent, since changes or updates of computation methods may lead to important deviations in future–year estimates and therefore misleading information about the effectiveness of particular measures (DEFRA, 2011; Giannouli et al., 2011). For example, preliminary experiments revealed important differences (up to 20%) in nitrogen oxides (NO_X) emissions for the Madrid metropolitan area depending on the road traffic emission model used (Borge et al., 2014).

This structure of an AQP can be associated to the two main IAM approaches: scenario analysis and optimization approach. It is, however, mainly related to the scenario analysis approach, which starts with the identification of control strategy measures as a result of air quality exceedances. These measures have to be translated to emission reductions and their impacts on the air quality, quantified using modeling tools. Policy implications, technical feasibility, resulting costs and environmental and health impacts are evaluated, but not within an integrated perspective. In case an optimization approach is used the cycle fully closed and measures, costs and benefits are integrated towards the optimization of the measures taking into account cost–efficiency aspects.

3. Characterization of the Reviewed Air Quality Plans

The literature review was focused on AQP developed by MS, but also included case studies reported in publications and information obtained from research projects. An overview of the reviewed AQP is firstly presented, then emphasis is given to the abatement measures adopted to improve the air quality, and thereafter a synthesis on the modeling methodologies used in AQP to assess the measures' impact is provided.

3.1. Overview of the AQP

Twenty AQP developed by European MS were analyzed. Table 1 includes the main characteristics of these AQP, namely region/ agglomeration and pollutants addressed, as well as the main considered aspects. Every AQP contain topics related to emissions and their impacts on air quality and health, although in the vast majority of them only the influence of the emission abatement measures on the air quality is quantified. Considered aspects in Table 1 are part of the Figure 1 components of a typical IAM structure.

Air pollution problems related to particulate matter of aerodynamic diameter less than 10 µm (PM_{10}), ozone (O_3), nitrogen oxides (NO/NO_2) and sulfur dioxide (SO_2) are the most addressed by the AQP. The same conclusion can be extracted from the European Commission (EC) assessment report of MS Plans and Programs (Nagl et al., 2007). In most cases, road traffic was identified as the main source of PM_{10} and NO_2 exceedances, followed by industry, commercial and residential sources. Nagl et al. (2007) also mention that SO_2 exceedances are mainly associated with industrial activity.

Air quality standards used in the AQP are based on the Directive 2008/50/EC (EC, 2008). PM_{10} has a daily limit value of 50 µg m^{-3} and cannot be exceeded more than 35 times in a calendar year. The maximum annual average for PM_{10} concentrations is 40 µg m^{-3}. For NO_2 an hourly limit value of 200 µg m^{-3} is defined, which should not be exceeded more than 18 times in a year. The annual average limit value of NO_2 concentration is 40 µg m^{-3}. Hourly and daily limit values are defined for the SO_2 concentration levels, respectively 350 µg m^{-3} and 125 µg m^{-3}. For these reference periods, the concentration levels should not be exceeded more than 24 and 3 times in a calendar year. For O_3, hourly information and alert thresholds are established, corresponding to 180 µg m^{-3} and 240 µg m^{-3}, respectively. However, since O_3 is a secondary pollutant formed in the troposphere from complex chemical reactions, it becomes necessary to act on the emissions of O_3 precursors such as NO_X and non–methane volatile organic compounds (NMVOC).

The costs for implementation (equipment and maintenance) of the abatement measures and the use of air quality modeling tools to evaluate the effects of the measures are taken into account in the majority of the AQP.

3.2. Measures adopted to improve the air quality

Abatement measures, classified as technical (TM) and non–technical (NTM), are used and evaluated aiming to quantify their reduction efficiency and costs of their implementation and operation. Technical measures are the so–called "end–of–pipe–technologies" and they neither modify the driving forces of emissions nor change the structural composition of systems or activities, but are applied to reduce emissions before being released in the atmosphere. European based averaged values are often used as a starting point for the definition of some TM. Non–technical measures reduce anthropogenic driving forces and can be related to people's behavioral changes (e.g. environmental education and awareness, car sharing) or to technologies that, reducing the energy demand, abate the fuel consumption (e.g. the use of high efficiency boilers or building thermal insulating coats). Different responses to the same NTM have been observed in different regions with a broad variation of the effect of each measure on pollutant sectoral emissions (Oxley et al., 2004; D'Elia et al., 2009; Giannouli et al., 2011).

In addition to the nature of the measures (TM and NTM), the spatio–temporal horizon for their application is also an important considered factor. Since the quantification of the measures impact is often conducted at agglomeration scale, the synergy and consistency between measures designed for different spatial levels (national, regional, local or even district) is ensured. When working at smaller territories, the local authorities take a very important role in the population awareness and creating links with the small and medium enterprises, contributing for reducing the uncertainties associated with the estimates.

Based on a simplified cost–efficiency analysis, measures are selected and prioritized for implementation in order to effectively provide a certain benefit (WHO, 2013). Priority measures are those which were estimated as more effective and with lower total implementation costs, taking into account the sum of both fixed and variable components. Fixed costs are associated with the investment (e.g. acquisition of equipment) and design/ construction of certain systems. The variable component includes the costs associated to the operation and maintenance of the measures (e.g. consumption of fuel, manpower), usually estimated in an annual basis. However, the costs quantification, particularly related to the proposed long–term measures, tends to have a higher degree of uncertainty by reasons linked to the evolution of the goods´ and services´ prices.

The definition of effective abatement measures to comply with the EU air quality limit values, within the prescribed period, is based on a previous characterization of sources to identify the geographic origin of pollutants and the contribution of sources responsible for the air pollution exceedances. The air pollution control strategies adopted in the reviewed AQP, in particular the abatement measures of pollutant emissions, are mostly focused on the road traffic sector, which is identified as the main source of PM_{10} and NO_2.

Table 1. *Main characteristics of some MS AQP*

Member States	Region/ Agglomeration	Pollutants	Considered Aspects [a]	Air Quality Modeling			References
				Model	Type	Comments	
Belgium	Antwerp	NO_2, PM_{10}, $PM_{2.5}$, SO_2, CO	1, 3, 4	Operational Prioritary Substances Model (OPS)	Lagrangian CTM	This model has been applied to obtain concentrations on a 1x1 km^2 grid covering the Flemish region in which Antwerp is located.	Mensink et al. (2003)
Denmark	Copenhagen, Aalborg, Aarhus and Odense	NO_x, O_3, PM_{10} and others	1, 3, 4	Danish Eulerian Hemispheric Model (DEHM)	Eulerian CTM	The model was applied at national scale (150 kmx150 km) using three nested domains with the following resolutions: Europe (50 kmx50 km); Northern Europe (16.7 kmx16.7 km); Denmark (5.6 kmx5.6 km).	Brandt et al. (2012) DCE (2013)
				Urban Background Model (UBM)	Urban background pollution model	–Calculations of urban background concentrations based on emission inventories with a spatial resolution of 1 kmx1 km, to be used as an input to the DEHM; –A simplified scheme including dispersion, transport and chemical reactions of NO_x with O_3 is considered.	
				Operational Street Pollution Model (OSPM)	Street canyon model	–Based on a combined plume and box model that can simulate in–street emissions and dispersion according to local building geometry and street configuration; –Air pollution estimation at 2 m height of selected streets.	
France	Marseille and Arles	NO_2, O_3, PM, SO_2, CO	1, 3	CHIMERE Model	Eulerian CTM	Multi–scale model designed from regional to urban level in order to produce O_3 forecasts (daily maximum value), aerosols and other pollutants (hourly data).	FRANCE (2013)
Germany	Berlin	NO_x, PM_{10}	1, 3	IMMIS–Luft	Street canyon model	The model has been used to assess the air pollution related to the road traffic.	Lutz (2009)
Greece	Athens	NO_x, NMVOC	1, 3, 5	Model for the Atmospheric Dispersion of Reactive Species (MARS/MUSE)	Eulerian CTM	Regional/local scale. No more information available.	Tourlou et al. (2002)
Ireland	Several regions	NO_x, O_3, PM_{10}, $PM_{2.5}$, SO_2, CO, CO_2, VOC and others	1, 2	n.a	n.a	No air quality modeling included.	U.S. EPA (2013)
Italy	Several regions	NO_x, PM_{10}, SO_2, hydrocarbons, heavy metals and others	1, 3, 4	n.a.	n.a.	n.a.	ITALY (2005) D'Elia et al. (2009)
Latvia	Riga	NO_2, PM_{10}, $PM_{2.5}$	1, 2	n.a.	n.a.	No air quality modeling included.	ECOREGION (2011)
Malta	Maltese Islands	PM_{10}, NO_2	1, 2	n.a.	n.a.	No air quality modeling included.	MEPA (2010)
Netherlands	Several regions	NO_x, PM_{10}, SO_2, CO_2 and others	1, 3	Operational Prioritary Substances Model (OPS)	Lagrangian CTM	High resolution (1 kmx1 km) for large–scale predictions of various air pollutants that are subject to European air quality norms.	Air4EU (2006) Priemus and Schutte–Postma (2009) NEAA (2010)
Poland	Several regions	PM, NO_2, SO_2, O_3, CO	1, 3	Global Environmental Multiscale and Air Quality (GEM–AQ) Model	Eulerian CTM	The model was applied with an horizontal resolution of 15 km over Europe, and an higher resolution, 5 km, over Poland (and surrounding countries).	Kaminski and Struzewska (2013)

Table 1. *(Continued)*

Member States	Region/ Agglomeration	Pollutants	Considered Aspects [a]	Air Quality Modeling			References
				Model	Type	Comments	
Portugal	Northern Region	NO_2, PM_{10}	1, 3	The Air Pollution Model (TAPM)	Eulerian CTM	The model was applied for an entire year and for three domains with different resolutions using the nesting approach: Iberian Peninsula (43.2 kmx43.2 km); Northern and Central Regions (14.4 kmx14.4 km); Northern Region (4.8 kmx4.8 km). The inner domain had an area of 120 kmx120 km.	CCDR–N and UA (2007)
	Braga Agglomeration	PM_{10}	1, 3				CCDR–N and UA (2010)
	Lisbon and Tagus Valley Region	NO_2, PM_{10}, SO_2	1, 2	n.a.	n.a.	No air quality modeling included.	CCDR–LVT (2006)
Romania	Bucharest	NO_2, O_3, PM_{10}, SO_2, CO	1, 3	CHIMERE Model	Eulerian CTM	Multi–scale model designed from regional to urban level in order to produce O_3 forecasts (daily maximum value), aerosols and other pollutants (hourly data).	ROMAIR (2010)
Spain	Barcelona metropolitan area	NO_2, PM_{10}	1, 3	Community Multi–scale Air Quality Model (CMAQ)	Eulerian CTM	Four nested domains were used to capture pollution processes from the continental to the local scale. The inner domain has 1 km^2 grid cells and temporal resolution of 1 hour.	Soret et al. (2011)
	Madrid	NO_2, O_3, PM_{10}, SO_2 and others	1, 3	Community Multi–scale Air Quality Model (CMAQ)	Eulerian CTM	Four nested domains were used to capture pollution processes from the continental to the local scale. The inner domain has 1 km^2 grid cells and temporal resolution of 1 hour.	MADRID (2012) Borge et al. (2014)
				Operational Street Pollution Model (OSPM)	Street canyon model	–Based on a combined plume and box model that can simulate in–street emissions and dispersion according to local building geometry and street configuration; –Air pollution estimation at 2 m height of selected streets.	
Sweden	Stockholm	NO_x, PM_{10}, CO_2	1, 3, 4	Danish Eulerian Hemispheric Model (DEHM)	Eulerian CTM	n.a.	EHA (2006, 2010)
United Kingdom	London	NO_2, PM_{10}	1, 3, 4	Pollution Climate Mapping (PCM) models	Urban background pollution model	Used to calculate urban (and rural) background concentrations for all pollutants on a 1 kmx1 km grid.	Mediavilla–Sahagun et al. (2002) DEFRA (2011)
	Manchester	NO_2, PM_{10}, SO_2, CO	1, 3	The NETCEN primary NO_2 model	Street canyon model	–One–dimensional representation of the interaction between NO_x and O_3 concentrations at roadside locations; –Results showed a good adjustment when compared with measurements	SCC (2005, 2006)

[a] *1: Costs for implementation (equipment and maintenance) of abatement measures, 2: Effectiveness of the measures in reducing emissions is assumed to be proportional to benefits on the air quality (using only monitoring indicators), 3: Impact on air quality of designed measures based on modeling (validation with reference observed values), 4: Air quality impacts on the human health 5 Air quality impacts on both human health and environment*

n.a. Information not available in the literature reviewed

There is a large diversity of abatement measures associated to road traffic. Classifying them into different categories facilitates their assessment. The measures´ classification reported by Nagl et al. (2007) was adopted here: technical, traffic management, public transport, traffic restrictions, road construction, speed reduction, street cleaning and others. Technical measures are closely related to technological improvements to reduce emissions, for example through the investment on the progressive introduction of electric and hybrid vehicles. Traffic management options are mainly taken to reduce the traffic in urban centers and to regulate the circulation and parking conditions. Within the public transport category, the incentive to displace to work/school using buses, trains, bicycles or even walking is promoted. Traffic restrictions in certain zones can be imposed as a function of the vehicle type (e.g. EURO norms, fuel type), time of day and during the most polluted days. The measures included in the road construction´s category intend to contribute for enlarging the public transport network, as well as to improve the traffic flow. Reducing speed limits contemplates specific speed restrictions regarding the access to urban centers and speed management on highways. The street cleaning measures, such as sweeping and wet cleaning of streets and pavements, are easy to implement, but requires a lot of manpower. Other control options that do not fall into the previously mentioned categories are, for example, designing urban mobility plans, car sharing initiatives and efficient driving training (Nagl et al., 2007).

Based on this road traffic measures classification, AQP were analyzed taking into account the regulatory character, the spatial application scale and the time horizon of the measures. Figure 2 shows the percentage distribution of the different measures´ categories by these three main aspects.

All measures included in the traffic restrictions and speed reduction categories are based on regulatory policies. On the other hand, technical, public transport and road construction measures are considered as behavior–based measures, because their implementation strongly depends on the public acceptance and of changing behaviors. For instance, technical measures effectiveness depends on the replacement by users of older fleet vehicles by greener alternatives.

Street cleaning options are taken at local scale, speed reduction policies are applied at regional level, and road construction measures cover different spatial domains, depending on the extension and construction type.

Moreover, speed reduction, street cleaning and public transport measures are expected to have effects within a short–term period. Road construction options, however, could only be evaluated at a longer–term, because the time for finishing the works also has to be taken into account.

Moving from road traffic measures to emission reductions implies quantifying the changes of emission values. National emission factors for different vehicle ages and circulation speeds can be used (e.g. Borrego et al., 2011). Another approach is based on correlations describing how the emissions from different vehicles change for different traffic conditions (EHA, 2006). However, the effectiveness of the abatement measures as well as the behavior of vehicle owners are key determinants of emission changes (DEFRA, 2011). Furthermore, in the last years, road traffic emissions have also been reduced due to the economic crisis, which lead to decreasing levels of traffic in the cities (MADRID, 2012).

Notwithstanding the strong efforts towards the road traffic sector, emissions from the industrial activity and the residential combustion sectors also contribute to high air pollution levels. In many countries, industrial installations operating licenses, defined in legal diplomas by activity area, comprise emission limit values and other requirements based upon the application of best available techniques (BAT). For instance, in the United Kingdom, between 2000 and 2009, NO_x emissions from the power energy sector were reduced by 27% and from other industrial combustion by 34% (DEFRA, 2011). Borrego et al. (2012) concluded that more efficient PM retention systems for the industrial sector could lead to reductions of PM_{10} emissions reaching up 50% for the wood and cork industries, which represents an average PM_{10} reduction of 17% for the entire Northern Region of Portugal.

Residential combustion is another important source of particulate matter emissions. The regulation of this sector, particularly the certification of equipment with lower PM_{10} emission rates, will contribute to air quality improvement (both outdoors and indoors). However, the implementation of this type of measure follows a complex process that needs the involvement of several entities and stakeholders and the reviewed AQP are not properly addressing this challenge.

3.3. Modeling methodologies

Different methodologies are used for the design and development of AQP, from simpler ones including the analysis of emission abatement scenarios using air quality models, to more complex ones, which include optimization approaches, taking also into account cost–efficiency aspects.

Air quality impact. Assessment of the impact of emission mitigation scenarios on the air quality is mainly based on a combination of information from monitoring networks and modeling results. Some AQP, however, just consider the monitoring network as spatially representative of the study domain (e.g. Lisbon Region, Riga, Malta). Nevertheless, as it was mentioned before, the use of models is currently encouraged by the AQD as a tool to support the decision making process and air quality management. They estimate pollutant concentrations in areas not covered by air quality stations, and are able to quantify the impact on air quality of projected emission scenarios.

Eulerian Chemical Transport Models (CTM) are the most used in the reviewed AQP (see Table 1), requiring as input data the emissions estimated for the several activity sectors, meteorological variables and initial and boundary conditions. Results from the ongoing EU research project APPRAISAL (APPRAISAL, 2013a) confirm this broader use of CTM within AQP. According to APPRAISAL (2013a) 40% of the AQP use Eulerian CTM, followed by Gaussian plume models (22%).

The current practice regarding emission input data is to use emission inventories based on both bottom–up and top–down approaches. However, due to the lack of detailed data, top–down methodologies are used based on spatial disaggregation techniques coming down to the municipal level or even to smallest functional units (e.g. parishes), by disaggregation factors, such as the population density.

In terms of meteorology, the large majority of the air quality models, depending on their application scale, use meteorological data obtained from mesoscale meteorological models. Given the models´ requirements and computational limitations (e.g. running time), it is common to use meteorological data for a short study period. Usually, these data are selected for different seasons, but always aiming to support the characterization of air pollution episodes. Meteorological measurements are also used, especially for street canyon and urban scale modeling.

Although initial and boundary conditions are mainly provided by larger scale models, the use of measured data at street level and at urban and local scales is also considered (DEFRA, 2011; MADRID, 2012; DCE, 2013).

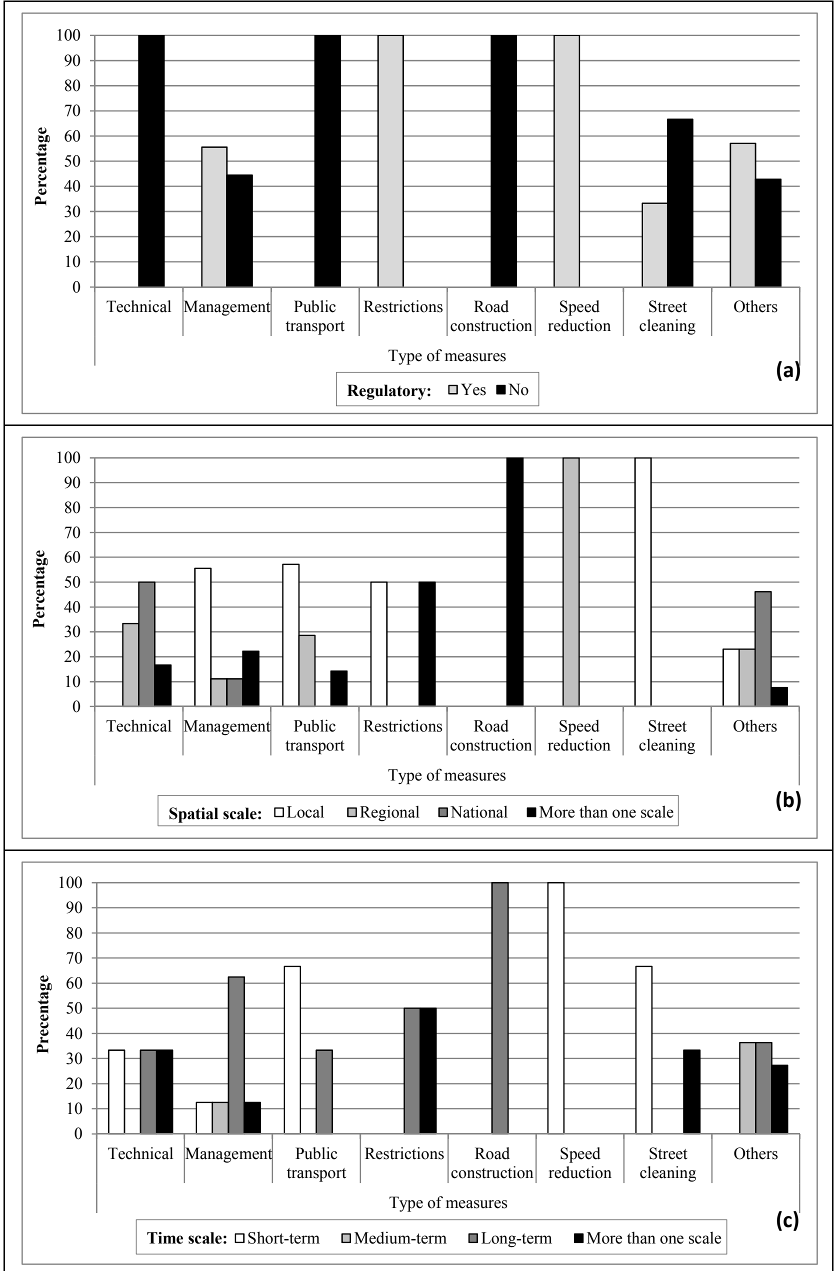

Figure 2. *Distribution of traffic sector measures by categories and taking into account:* ***(a)*** *regulatory or non–regulatory aspects,* ***(b)*** *the spatial scale of the measure application, and* ***(c)*** *the application time scale.*

The air quality modeling system can be applied to different nested domains to assess the set of emission reduction measures (scenario analysis) or to establish source–receptor relationships as part of the IAM (optimization approach) (APPRAISAL, 2013b). However, this procedure must be conducted very carefully, because it has been long recognized that in a typical urban environment, transport and dispersion of air pollutants are governed by processes that occur between the micro/local and mesoscales, while their levels may also be affected by transformation processes and by long–range transport, i.e. processes occurring at the regional scale.

Economic evaluation. The economic analysis allows identifying alternatives/measures to improve the air quality, weighting their consequences or effects against their costs. For this purpose, a comprehensive assessment of all air pollution impacts, also expressed as externalities, is required (WHO, 2013). Externalities generated from air pollutants are related to the social welfare and economy, and can include both negative economic effects (damages) and positive economic effects (benefits, also described as avoided external costs) on the environment and health (EC, 2005). If benefits are larger than costs, the policy or measure is more effective and beneficial for improving air quality. Normally, the comparison of two or more measures is examined through cost–effectiveness and cost–benefit analyses.

The cost–effectiveness assessment (CEA), in accordance to the AQD, is used to compare the relative costs and corresponding air quality and/or heath impact associated with the implementation of measures. Considering the health effects, typically the CEA is expressed in terms of the ratio between a gain in health from a measure (e.g. increased life expectancy) and the cost associated to its implementation. The cost–benefit assessment (CBA) differs from the CEA, because effects (benefits) and costs of the measures are accounted in monetary value. However, this evaluation is not a straightforward procedure since many of the air pollution effects have no market value (Belhaj and Fridell, 2010).

These types of assessment are included in some AQP analyzed here, namely those for Antwerp, Athens, Lisbon and several regions of Denmark, by the application of the Externalities of Energy (ExternE) methodology. This methodology provides a framework for obtaining impacts expressed in different units (e.g. physical–health effects), following a CEA, which can be converted to a common unit (monetary values) in order to make a CBA (EC, 2005). In terms of calculation, the ExternE comprises an Impact Pathway Approach (IPA), which allows to get the exposure of sensitive receptors (e.g. population) using an exposure–response function (e.g. cases of asthma due to increase in O_3 levels). Then the valuation of these impacts is estimated in monetary terms (e.g. monetary value of an asthma case). The health impacts are highlighted because they contribute to the largest part of the damage estimates. This finding is shared by public health experts, linking the air pollution, even at current ambient levels, to worsening morbidity (especially respiratory and cardiovascular diseases) and premature mortality (e.g. years of lost life) (EC, 2005). Costa et al. (2014) describe how health can be integrated on air quality assessment. Estimated costs of the treatment of diseases, including hospitalization and willingness–to–pay are two of the commonly used indicators.

Equation (1) shows the parameterization considered for calculating the emissions impact per air pollutant from a specific source or sector taking into account the abatement measures package included in AQP (Tourlou et al., 2002; EC, 2005; Brandt et al., 2012):

$$\Delta I_{cases,\,i} = CRF_{i,\,p} \times \Delta C_{\mathrm{p}} \times Pop \qquad (1)$$

where $\Delta I_{cases,i}$ is the response as a function of the number of the unfavorable implications (cases) over all health indicators (i=1,..., n) avoided or not. The resulting physical impacts are translated to monetary values (damage costs), in order to be properly considered in the decision–making process. $CRF_{i,p}$ is the correlation coefficient between the pollutant p´s concentration variation and the probability of experiencing or avoiding a specific health indicator i (Relative Risk), ΔC_p is the change in the pollutant p´s concentration after the adoption of abatement measures (emission scenarios), Pop is the population units exposed to pollutant p.

The pollutants concentration and population data are combined to estimate the human exposure, and then, the impact coefficient ($CRF_{i,p}$) is calculated using an exposure–response function (ERF), expressed as Relative Risk (RR) derived from epidemiological studies. Health indicators include all mortality and morbidity effects associated with the exposure to air pollutants, of which a greater significance is attributed to particulate matter (EHA, 2006).

The resulting benefits are often translated to the cost required for the unitary reduction of the emissions of each air pollutant considered. However, a situation which occurs regularly when the available budget is known, is the evaluation of the potential emission reduction achieved through the adoption of specific measures (Tourlou et al., 2002).

Integrated assessment. Integrated assessment jointly addresses the environmental and health impacts of the mitigation measures, as well as their implementation costs and the economic quantification of damages/benefits. Local and regional IAM are available, although the current assessment and planning within AQP is mainly based on scenario analysis approaches through the application of air quality models. The option for optimization approaches, despite their more limited use in AQP, is recommended to fully respond to the AQD. In the IAM optimization approach the emission reduction measures are selected by an optimization algorithm assessing their impact on air quality, health exposure and implementation costs (APPRAISAL, 2013b). Such optimization algorithm requires thousands of air quality assessments, which makes impractical the application of an air quality system due to the computation time involved. To overcome this problem, tens to hundreds of simulations are processed to identify simplified emissions–air quality links (source–receptor relationships) able to capture the specific features of a region. Linear functions to model this link are already often applied at the European and national scales. At regional level or at higher spatial resolutions it is advisable to properly model nonlinear dynamics in the formation and accumulation of secondary pollution (APPRAISAL, 2013a).

These IAM tools need data from the emission sources, namely emission inventories and their contribution to atmospheric concentrations and human exposure, but also emission control measures and their costs, in the sense of exploring strategies that permit a reduction of emissions (Oxley et al., 2004; Carnevale et al., 2012). The great advantage of these tools is the ability to determine the consequences of different assumptions and simultaneously interrelating different factors. Their effectiveness is limited by the quality and character of the assumptions and input data (Mensink et al., 2003; Reis et al., 2010; Carnevale et al., 2012).

Taking advantage of the added value of these tools, some European MS have already applied IAM to support the preparation of AQP. The USIAM (Urban Scale Integrated Assessment Model) and the AURORA modeling system (Air quality modeling in Urban Regions using an Optimal Resolution Approach) were used in the United Kingdom (London metropolitan area) and in Belgium (Antwerp), respectively.

The USIAM (Mediavilla–Sahagun et al., 2002) is an integrated assessment tool developed to quantify the primary PM_{10} contribution, requiring the integration of information on the sources and pollution imported into the city, on the atmospheric dispersion and resulting concentrations relative to air quality standards, and on costs and benefits of different options for emission reduction. To predict the impact of emission control strategies, USIAM evaluates the implementation of different scenarios.

The AURORA system (Mensink et al., 2003) is based on the same principle of USIAM. It is composed by various modules, such as health effects, economical aspects, scenario module and AQD limit values. The effects on the health and ecosystems degradation are assessed through dose–response functions using the ExternE methodology (EC, 2005), and then costs are estimated. A scenario analysis module allows decision makers to determine the best measures to improve the air quality in both quantitative and qualitative ways.

4. Limitations and Best–Practices

The use of AQ models to support the development of AQP is an advantage, as they simulate atmospheric processes establishing causal relationships. In other words, air pollution modeling can give a more complete deterministic description of the air quality problems, including an analysis of factors and causes (e.g. emission sources, meteorological processes, physical and chemical changes), and some guidance on the implementation of mitigation measures (Daly and Zannetti, 2007), grounded in cost–effectiveness analyses.

In most cases, the impact of these measures on air quality is assessed using mesoscale Eulerian air quality modeling systems. Despite a satisfactory performance of these models, at the urban scale weaknesses are identified by the scientific community. For example, strong concentration gradients of NO_2, usually associated to high road traffic flows, cannot be reproduced by mesoscale Eulerian models, since large concentration variations typically exist within the extension of a grid cell. In order to depict street level concentration gradients, local–scale tools are needed, either high–resolution flow models that consider the buildings or semi–empirical street canyon models able to capture this local variability. To this respect, Computational Fluid Dynamic (CFD) models are very computationally expensive and can only be applied to spatially and temporally restricted domains.

At emission inventory level, much work still needs to be done at the urban scale. This is probably the most relevant critical aspect to characterize air pollution levels in large cities, because an accurate knowledge on emissions from the main sources largely dictates the air quality management policies to adopt (Air4EU, 2006). Consistency between emission inventories developed at different scales, based on both bottom–up and top–down approaches, is an objective not accomplished yet (APPRAISAL, 2013a).

Controlling photochemical and particulate matter pollution implies reducing precursor gases and particulate matter emitted by human activities. Nonetheless a fraction of precursor gases and particles is emitted by natural processes and neglecting it when testing a control strategy could lower efficiency or even produce opposite effects.

Another important aspect, rarely addressed in AQP, is related to an integrated assessment perspective, which should include an economic analysis of the emission reduction measures, quantifying the total investment and human health and environmental effects resulting from exposure levels to pollutants. The inherent uncertainties in damage estimates, nevertheless, have generated quite controversy regarding the usefulness of damage costs. In response to this critical issue, it is referred that even an uncertainty by a factor of three is better than infinite uncertainty (EC, 2005). Other possibility to explore the uncertainties in the context of specific decisions is to carry out sensitivity analyses and check whether the decision (e.g. implementation of technology A instead of technology B) changes with different assumptions (e.g. discount rate, valuation of life expectancy loss) (EC, 2005; U.S. EPA, 2013).

For these reasons, efforts for the development of a consistent and flexible approach that allows cost–efficiently determining air quality levels and their impacts at urban/local scale are still required. IAM can be an option, but weaknesses and strengths should be better exploited. In particular the effectiveness of both technical and non–technical measures in different spatial domains in a comprehensive multi–scale system has to be addressed, as well as the synergy between measures. Moreover, the selection of measures should be guided too by the existing operational means and keeping in mind their public acceptability.

5. Final Comments

Given the current relevance of the urban air quality, emission abatement strategies for its improvement are crucial. In this context, a legislative European framework has been established obliging Member States to design air quality plans (AQP) and encouraging the involvement of local authorities and stakeholders in order to meet the air quality standards within a specified temporal horizon.

The majority of the analyzed AQP mainly considers the impact of emission abatement measures on the air quality. The use of AQ models, with monitored data, is viewed as the best currently available approach to understand the response of the atmosphere to different air pollution control measures, providing essential information on the maximum feasible air quality improvement. However, the link between the resulting air quality state and its consequences for health and related cost–efficiency analysis are often neglected, principally in a quantitative way.

Taking into account the limitations of the currently available assessment methods as well as the best–practices identified for quantifying the overall impact of the measures, the path to follow in future AQP studies should be grounded on integrated assessment methodologies, constituting these tools an added value for the decision making process on air quality management.

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