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Air quality mitigation in European cities: Status and challenges ahead

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ABSTRACT

Cities are currently at the core of air quality (AQ) improvement. The present work provides an overview of AQ management strategies and outcomes in 10 European cities (Antwerp, Berlin, Dublin, Madrid, Malmö, Milan, Paris, Plovdiv, Prague, Vienna) in 2018, and their evolution since 2013 (same cities, plus Ploiesti and Vilnius), based on first-hand input from AQ managers. The status of AQ mitigation in 2018, and its evolution since 2013, were assessed. While results evidenced that the majority of mitigation strategies targeted road traffic, emerging sources such as inland shipping, construction/demolition and recreational wood burning were identified. Several cities had in 2018 the ambition to continue decreasing air pollution concentrations to meet WHO guidelines, an ambition which had not yet been identified in 2013. Specific needs identified by all of the cities assessed were tools to quantify the effectiveness of mitigation strategies and for cost-benefit analysis, as well as specific and up to date technical guidance on real-world road vehicle emissions. The cities also requested guidance to identify mitigation measures promoting co-benefits, e.g., in terms of AQ, climate change, and noise. Support from administrations at local-regional-national-EU scales, and especially involving local policy-makers early on in the air quality management process, was considered essential. This work provides insight into the drivers of successful/unsuccessful AQ policies as well as on the challenges faced during their implementation. We identify knowledge gaps and provide input to the research and policy-making communities as to specific needs of cities.

1. Introduction

Exposure to ambient air pollution is the single largest environmental health risk at global scale (Gakidou et al., 2017), and there is currently no evidence of a threshold below which no adverse health effects occur (Kelly and Fussell, 2015; Pope et al., 2019). In the EU, air pollution is estimated to cause > 400.000 premature deaths per year (EEA, 2019a), with the largest exposures occurring in cities: for example, for fine particulate matter ($PM_{2.5}$) 8% of the EU28 urban population was exposed to levels above the EU annual limit value in 2017, and 77% to concentrations exceeding the World Health Organization (WHO) air quality (AQ) guidelines (EEA, 2019b).

Despite the decreasing trends in air pollutant concentrations at regional and local scales in Europe (Cusack et al., 2012; Guerreiro et al., 2014; Maas and Grennfelt, 2016; Querol et al., 2014; UNECE, 2016), air pollution continues to cause respiratory and cardiovascular disease and lung cancer (EC, 2019a). In the first decade of the 21st century across Western Europe air pollutant concentrations (mainly, PM_{10} and NO_2) in cities did not decrease in parallel to the mitigation actions undertaken at European scale, raising questions about (a) the effectiveness of the EU regulatory framework at urban scale, (b) the impact of actual measures implemented (Brunekreef et al., 2015; Harrison et al., 2014, 2008), and (c) the influence of other factors such as new particle formation, meteorology, or hemispheric and background contributions.

As a result, cities are currently at the core of AQ management, aiming to enhance the urban environment and quality of life of citizens, while adapting to the changing climate. However, AQ managers must deal with challenges such as constantly updating technical knowledge (e.g., real-world emissions of certain types of on-road engines), the lack of information on the effectiveness of specific mitigation measures (e.g., TiO_2-based solutions), or the complexity linked to the implementation of regulations by different (levels of) administrations. In order to understand the drivers and challenges of AQ improvement in European cities, the European Environment Agency (EEA) undertook the Air City Pilots in 2013 (EEA, 2013) and 2018 (EEA, 2018), analysing with 12 and 10 major European cities, respectively in each year, their AQ mitigation strategies. The present work aims to integrate the results to provide an overview of AQ management strategies and outcomes in

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European cities in recent years, and the evolution of the strategies in a 5-year period. It should be noted that the analysis refers to the mitigation strategies, not to the air pollution concentrations monitored, and therefore the air pollution scenarios in each city in 2013 and 2018 are not presented or assessed. The assessment of air pollution mitigation strategies will provide understanding on the drivers of successful (and unsuccessful) AQ policies as well as on the challenges faced during their implementation. The ultimate goal of the pilots was to identify future directions and knowledge gaps, and to provide input to the research and policy-making communities as to the needs of the cities.

2. Methodology

The cities were selected so as to ensure a representative sample of the diversity of Europe's urban areas. The selection aimed at including cities from different parts of Europe, of different population sizes, with different administrative traditions, and with a variety of sources of pollutants (EEA, 2013). Air quality questionnaires were distributed to AQ representatives from 12 European cities (Antwerp, Berlin, Dublin, Madrid, Malmö, Milan, Paris, Ploiesti, Plovdiv, Prague, Vienna and Vilnius) in 2013, and similar questionnaire again in 2018 (to the same cities except for Ploiesti and Vilnius) (EEA, 2018, 2013). In addition, in 2013 the Time Extension Notifications and the Plans and programmes forms were analysed (ETC/ACM, 2013a, 2012). The questionnaire on AQ management practices for 2013 is published in the Annex of (ETC/ACM, 2013b), while the 2018 version is unpublished due to confidentiality reasons. The questionnaires requested information regarding AQ management practices, AQ monitoring networks, local emission inventories and modelling, public information, and need for further guidance. After collecting the replies, additional information was obtained from city representatives by means of face-to-face meetings and online webinars. Finally, results were discussed in two face-to-face workshops with all of the city representatives. The individual initiatives were published in two EEA reports (EEA, 2018, 2013). The data obtained are integrated in the present work, extracting the situation in 2018, the evolution since 2013, and the challenges ahead focusing on AQ monitoring and modelling in cities, mitigation strategies implemented and their effectiveness, and further guidance needed.

3. Results

3.1. Status of air quality monitoring and modelling in cities

All of the cities replied to the questionnaires and participated in the face-to-face meetings/workshops and online webinars. In 2013, the cities operated their air quality networks in accordance with the EU Ambient Air Quality Directive, regarding the number of monitoring stations. Aside from regulatory compliance, city experts reported that increasing the number of sampling points, especially for NO_2 and PM (both $PM_{2.5}$ and PM_{10}), could be beneficial for testing and monitoring the effectiveness of abatement strategies. In fact, Antwerp, Dublin, Madrid and Prague increased the number of sampling points between 2013 and 2018 with the aim to provide more representative estimates of population exposure and better represent the AQ situation (EEA, 2018). The main concerns in 2013 were issues regarding the location of monitoring stations, specifically that guidance was needed for macro- and micro-siting criteria (EEA, 2013). This issue was not mentioned anymore by the cities in 2018. In addition, in 2018 most of the cities had introduced or increased the input from external experts (for example through LIFE projects, https://ec.europa.eu/easme/en/life), and 4 out of 10 cities had increased the number of parameters monitored (non-regulated pollutants such as particle number concentration – ultrafine particles, black carbon – BC, real-time chemical composition, visibility, and ammonia) (Table 1, top).

In terms of air emission inventories and AQ modelling, in 2013, all of the 12 cities had emission inventories with the exception of Dublin, where they were being created. The available inventories had been compiled using a variety of methodologies, hindering comparability between cities and with national or regional inventories. The same was true for the types of models used. Finding available data for relevant sources, especially for traffic, was identified as a difficulty (Castell et al., 2015; EEA, 2018). In 2018, the 10 cities consulted reported improvements in emission inventories, including implementing an AQ model in the only city (Dublin) not having one in 2013 (EEA, 2013). Seven cities had improved at least one of the following: (i) methodologies and emission factors, (ii) number of pollutants modelled, (iii) improved source quantification, or (iv) other improvements to input data. New emission sources included in the models were inland waterways, local heating and local traffic; while new pollutants included were polycyclic aromatic hydrocarbons (PAHs), benzo(a)pyrene, elemental and organic carbon, soot or black carbon (BC), and $PM_{2.5}$.

3.1.1. Challenges ahead

The interest in monitoring emerging and non-regulated parameters (ultrafine particles, black carbon, ozone precursors, ammonia, visibility) was strong in Antwerp, Berlin, Madrid, Malmö, Milan, Paris, and Vienna. These novel parameters were seen as useful tracers of specific emission sources and thus valuable to monitor the effectiveness of targeted mitigation strategies. The cities supported that these novel parameters should be regulated and requested clear guidance regarding monitoring protocols if or once they are regulated. In parallel, cities had initiated implementations of indicative monitoring methods by 2018: for example, the city of Berlin used passive NO_2 dosimeters, black carbon and aerosol chemical speciation to monitor the effectiveness of abatement measures for specific emission sources (mainly, road traffic and biomass burning). Citizen science and sensing approaches were also tested by some of the cities (Antwerp, Madrid, Paris), but technical and public information challenges still remained regarding especially low-cost technologies (including also low-cost samplers, e.g., diffusion tubes). Furthermore, cities such as Paris were dedicating continued efforts to testing and validating sensor technologies (e.g., AIRPARIF-AIRLAB microsensors challenge, http://www.airlab.solutions/en/projects/microsensor-challenge-edition-2019).

In terms of AQ modelling, the main technical challenge remaining after 2018 was the lack or low quality of the input data (EEA, 2018), identified by 7 cities (Table 1, bottom). Additional challenges were the lack of technical infrastructure (e.g., long computational times; 5 cities) and lack of fugitive emissions as input to the models (5 cities). At least 4 cities indicated having difficulties with estimating background concentrations and with lack of precision of the models (reported as under- or overestimations of pollutant concentrations). These issues are thus gaps which could be filled by increased action at the science-policy interface.

3.2. Air quality management practices

3.2.1. Current and emerging emission sources

An evaluation of the mitigation measures implemented and planned in the cities provided relevant insights into the key emission sources causing AQ degradation (Table 2). In 2013 the main emission sources targeted by the measures were road traffic (in all of the cities), residential heating (9 cities), and industry (8 cities). The relevance of road traffic continued in 2018, when all of the cities reported a wide variety of measures to improve urban mobility (e.g., speed limits, congestion charges, promotion of cycling). Road traffic was the main target of measures as it is identified as the main contributor in the cities by means of source apportionment studies and dispersion models (e.g., (Karagulian et al., 2015; Viana et al., 2008), as well as the frequent exceedance of the EU limit values NO_2 (EEA, 2019a). A limited number of measures focused on industrial and residential heating emissions, probably as a result of the effectiveness of the measures implemented or foreseen in 2013 and their structural nature (e.g., displacement of

Table 1
Top: changes implemented in the local air quality networks between 2013 and 2018, and cities implementing each of them, referring to the 10 cities participating in both assessments (Antwerp, Berlin, Dublin, Madrid, Malmö, Milan, Paris, Plovdiv, Prague, and Vienna). Bottom: technical challenges remaining regarding the use of air quality models by cities.

Changes implemented	Cities
No changes	Vienna
Increased nr. of qualified operators	Dublin, Milan,
Site re-location	Milan, Plovdiv, Prague
Increased nr. of sampling points	Antwerp, Dublin, Madrid, Prague
Increased nr. of parameters monitored	Antwerp, Madrid, Malmö, Milan, Paris
Support from external experts	Antwerp, Berlin, Dublin, Madrid, Prague
Other changes	Antwerp, Berlin, Dublin, Malmö, Milan, Paris
Technical challenges remaining for AQ models	Cities*
Other	Berlin, Malmö
Model specifications**	Milan, Plovdiv
Difficulty to interpret results	Madrid, Prague
Difficulty estimating background	Malmö, Paris, Plovdiv, Prague
Over/underestimations	Berlin, Madrid, Milan, Vienna
Lack of fugitive emissions	Malmö, Paris, Plovdiv, Prague, Vienna
Long computational time	Berlin, Madrid, Milan, Prague, Vienna
Quality of input data	Berlin, Madrid, Malmö, Milan, Plovdiv, Prague, Vienna

* Antwerp, Dublin: no challenges reported, modelling tasks external contract.
** Model specifications: Technical difficulties, such as how to account for urban topography or coupling and sub-grid scale processes.

industrial plants outside the urban area and changing the heating installations in buildings), which resulted in lower AQ impacts of these sources in the urban areas in 2018. This trend was maintained when looking into the future: measures which were in the planning phase in 2018 continued to focus on urban mobility, followed by residential heating mainly due to the increase in woodstove use in urban areas (EEA, 2016).

Emerging emission sources were also identified in 2018, specifically inland shipping, and construction and demolition activities. The term "emerging" here is used from an air quality management perspective, i.e., the relative relevance of these sources was seen to increase in the Pilot cities and therefore they started to be targeted by AQ managers. Several cities (Berlin, Antwerp, Dublin, Vienna, Prague) expressed major concerns regarding inland shipping, especially based on its rapid and recent growth due to tourism, its emissions close to the citizens in the inner city, and to the lack of emission standards. This results in paradoxes such as the fact that vessels may be allowed in areas of the city restricted to vehicular traffic (e.g., low emission zones, as in the case of Antwerp). Construction and demolition works were also identified as major PM emission sources in growing cities such as Berlin and Vienna. Finally, recreational wood burning was specifically noted as an emerging source in the cities of Milan and Paris. Regional-scale transport of pollutants was also a major source of concern regarding urban $PM_{2.5}$ in Milan (from agriculture) and Vienna (from wood burning in neighbouring countries) (EEA, 2018). Agriculture was considered a relevant source of secondary particles ($PM_{2.5}$) in other cities as well (e.g., Antwerp, Paris), even though it was not targeted by dedicated mitigation strategies at urban-scale.

3.2.2. Mitigation strategies implemented

The criteria reported by the cities for the selection of measures were, in 2013:

- Effectiveness in emissions reduction: Berlin, Dublin, Milan, Ploiesti, Plovdiv
- Legal feasibility/competences: Antwerp, Berlin, Madrid, Paris
- Economic and social proportionality: Berlin, Antwerp, Vilnius
- Co-benefits (with climate change mitigation, noise, etc.): Milan, Prague, Vienna
- Technical feasibility: Berlin, Vienna
- Previous experiences (failed or successful): Dublin
- Contribution of sources: Berlin
- Effect on air quality: Berlin
- Quickness in results: Malmö
- Political and public acceptance: Vienna

Thus, aside from the effectiveness of the measures, the criteria reported by most cities were legal aspects (competences, etc.), cost, and optimising the benefits (through co-benefits).

Fig. 1 summarises the main types of mitigation strategies implemented by the cities. Major concerns before and after 2018 were road traffic and urban mobility, which were targeted by $>$ 50% of the measures implemented in in each city. In 2018, 9 and 5 cities exceeded the NO_2 and PM_{10} annual limit values (respectively; and 8 and 3, respectively, in 2013), therefore additional measures were proposed (although not all of them fully implemented in 2018) targeting traffic and aiming for behavioural change:

- New vehicle access restrictions in city centres: temporary bans for specific vehicle types, e.g. car-free days in Paris, full ban of diesel vehicles in Berlin, Madrid, Milan and Paris, and potentially vehicle labelling strategies regulating city access in Berlin. The fact that vehicle bans may shift traffic intensities to other areas (e.g., ring roads) was acknowledged as a limitation of this kind of measure. This was also addressed in (EC, 2019b).
- Technological improvements by retrofitting and promoting e-

Table 2
Emission sources targeted by air quality mitigation strategies in the cities assessed.

	Sources targeted
Measures implemented prior to 2018	Urban transport, residential heating, industry
Measures implemented in 2018	Urban transport, residential heating, industry, energy efficiency, shipping
Emerging sources identified in 2018*	Inland shipping, construction/demolition, recreational residential heating, road traffic, wood burning

* Measures were in planning phase, in 2018, for these emerging sources.

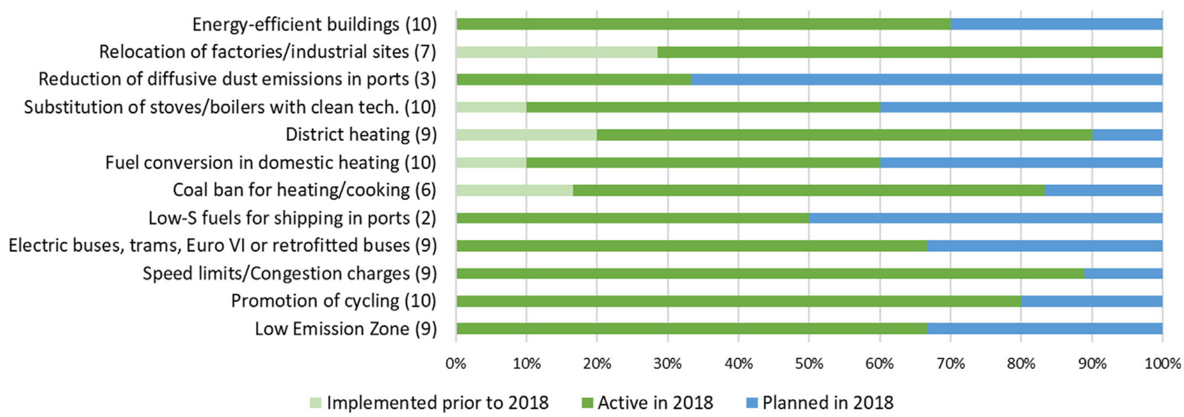

Fig. 1. Percentage of the 10 cities participating in both pilots (Antwerp, Berlin, Dublin, Madrid, Malmö, Milan, Paris, Plovdiv, Prague, and Vienna) in which mitigation/adaptation strategies were in place prior to 2018, in 2018, and being planned in 2018. In brackets, the number of cities implementing each measure.

mobility: examples were a retrofitting programme for municipal heavy-duty vehicles (Euro V garbage trucks) in Berlin, and electric buses and e-bikes (Berlin, Madrid, Milan, Paris, Vienna,).
- Modal shift towards cleaner mobility: designating increased public space for bicycles, pedestrians and public transport, with e.g., bike and car sharing (Madrid, Milan, Prague), construction of new metro lines (Antwerp), smart cities with metro-network and economic incentives for public transport (Vienna), and increased investment in public transport and bike lanes (all).

In addition to these traffic-related measures, Berlin and Vienna addressed emerging sources. Berlin implemented retrofitting of construction machinery and inland cruise ships with diesel particle filters and setting up emission criteria for non-road construction machines and cruising vessels. In Vienna, an innovative *environmental zone* for off-road machinery was set up in areas with high PM values.

Strategies were also envisaged to mitigate exposures. Antwerp, Berlin, Malmö, Paris or Vienna aimed to reduce exposures of vulnerable population groups (e.g., children, elderly) by promoting the construction of new day-care centres in cleaner areas of the city, and by introducing AQ in early stages of urban planning schemes concerning sensitive infrastructures, e.g. schools, homes for the elderly. Urban space management was also reported by Madrid, Paris and Vienna, e.g., forward-looking urban planning such as including public transport infrastructures at the earliest stages of urban development (e.g. during construction; Vienna).

Finally, mitigation strategies also involved innovation:

- Initiatives such as StadsLab2050 in Antwerp, or AirLab in Paris (http://www.airlab.solutions/), which foster the ideation and implementation of creative solutions.
- Using a *green tool* providing insight into the benefits of urban green space, in Antwerp (https://vito.be/en/news/antwerp-green-tool).
- Implementing citizen science initiatives (Antwerp, https://curieuzeneuzen.be/; and Madrid), as a tool for awareness raising in the policy-making community as well as for citizens.

3.2.3. Challenges ahead

Different types of challenges were reported. Legal challenges, mainly, administrative competences and collaboration (or the lack of it) between local, regional and national authorities were issues in 2013 and in 2018. One example was the finalisation of the ring road around Prague, allowing implementing the low emission zone, which was approved by national and regional authorities and subsequently appealed to court by district authorities, NGOs and citizens. Another challenge, highlighted in 2013 and 2018, was the lack of competences regarding financial mechanisms which could be key to solving the diesel problem and potentially minimising urban NO_2 exceedances, but which were not always within the competences of city administrations. Financial mechanisms and political stability were still issues, as the availability of funding schemes is essential for the implementation of measures, while changes in governments may lead to the withdrawal/delay of plans approved by previous administrations. Public opposition remained a challenge in terms of opposition to certain mitigation measures.

Other challenges such as lack of human resources or technology, and cultural aspects, were seen as less relevant in 2018. Technological challenges as the need for better modelling tools to address fine-scale air pollutant variability (e.g., for urban NO_2 concentrations) and for episode forecasting were highlighted by Berlin, Madrid, Prague, Vienna in 2018. One alternative proposed was the use of meteorological models as a potential forecasting tool for the purpose of public information, but not for the design or evaluation of mitigation measures. Other emerging technical challenges were the detection of fraudulent practices (e.g., tampering with exhaust filters) and policy implementation (e.g., for the enforcement of low emission zones linked with the registration of license plates for access control, in Madrid, Milan, Paris). Overall, all of the cities continued to agree that structural measures are preferable and more necessary than short-term strategies.

Two very specific technical challenges were identified in 2018. First, the uncertainty regarding road transport emissions, for example real-world emissions of Euro-6 vehicles, the efficiency of natural gas light-duty vehicles, or the emissions from LNG in comparison to Euro-6 for trucks. Detailed technical information would be necessary to improve national, regional and local emission inventories as well as to design and implement potential traffic bans. The second challenge, reported also in 2013, referred to residential emissions: technical guidance is necessary to identify the types of residential stoves and boilers which should be incentivised, in an attempt to avoid the conflict between AQ and climate policies. The cities highlighted that social inequality remains a challenge due to access to cleaner stoves and fuels, even when subsidies were offered.

Finally, additional challenges detected were growing population and urbanisation, lack of robust data and studies on emissions and impacts of measures, difficulties in the integration of policies, as well as citizen engagement and public awareness raising.

3.2.4. Effectiveness of mitigation measures

Understanding and communicating the benefits and costs of mitigation measures is essential when addressing policy-makers and the general public. Messages such as the health benefits of specific measures, e.g. in terms of premature mortality avoided, and their costs (in monetised estimates), are more meaningful to the general public and stakeholders than air pollutant reductions (in $\mu g/m^3$). These messages are thus more likely to receive support and facilitate the implementation of air pollution mitigation measures.

Quantitatively estimating the effectiveness of mitigation strategies to reduce air pollutants and health impacts was considered a complex issue in 2013 and 2018, from an AQ monitoring perspective. This is due to the influence of simultaneous factors such as meteorology, urban design, background contributions, and the combined effect of other measures and emission sources (Baldauf et al., 2019; Feng et al., 2019). Multidisciplinary approaches can better assess the co-benefits for human health and provide a justifiable basis for establishing mitigation policies and public health actions (Kim et al., 2020; Vrontisi et al., 2016). Modelling tools, from the perspective of the cities, are useful to assess relative trends (Jeanjean et al., 2017) and also assess the effect of different mitigation measures planned, but not suitable to quantify absolute changes in air pollutant concentrations. Despite this, some successful case studies are available for specific measures in cities such as Berlin (e.g., quantification of the AQ improvement due to the low-emission zone and to reduced speed limits; Lutz, 2018).

Health impact assessment (HIA) to estimate health benefits (e.g., premature mortality and morbidity avoided) was considered a useful tool to understand the effectiveness of measures, according to the city representatives: (a) in terms of costs (or disability-adjusted life years, DALYs); (b) for comparison between measures; and (c) for communication purposes. Comparability between results should be ensured and their uncertainty communicated. Online tools such as AirQ+ (http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/airq-software-tool-for-health-risk-assessment-of-air-pollution; WHO) and case studies of scenario analyses for specific AQ measures (Castro et al., 2017; Lee et al., 2019; Malmqvist et al., 2018; Velders et al., 2020; Viana et al., 2020) available in the literature were valued by the cities.

Fig. 2 shows that the majority of the cities consulted did initially not carry out cost-benefit analyses. However, they showed an increasing interest in this type of analysis between 2013 and 2018, as the number of cities implementing cost-benefit analyses increased. Different degrees of analyses were implemented: the increase in cities quantifying the effects of measures was relatively larger than that of those quantifying their costs, and that of those implementing cost-benefit analysis. The most frequently used tools for this quantification were assessments based on local AQ monitoring network data, followed by emission analysis and urban indicators (e.g., vehicle fleet composition), and modelling tools (Fig. 3). Co-benefits such as AQ improvements for downwind rural regions were, so far, not taken into account.

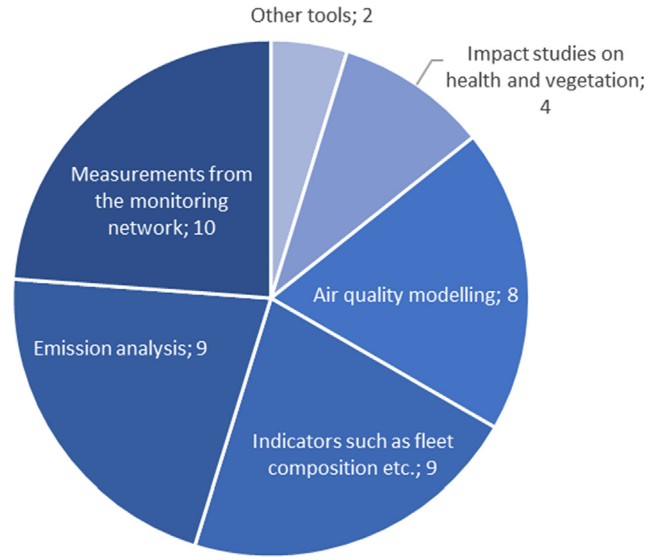

Fig. 3. Types of tools (and the number of cities using them) to estimate the effects of air pollution mitigation measures, in 2018.

3.2.5. Challenges ahead

Three main reasons for the absence of quantitative cost-benefit analyses were reported by the cities both in 2013 and 2018: the lack of user-friendly and comparable methodologies, their uncertainty, and the limited experience of AQ managers with this kind of tools. The cities

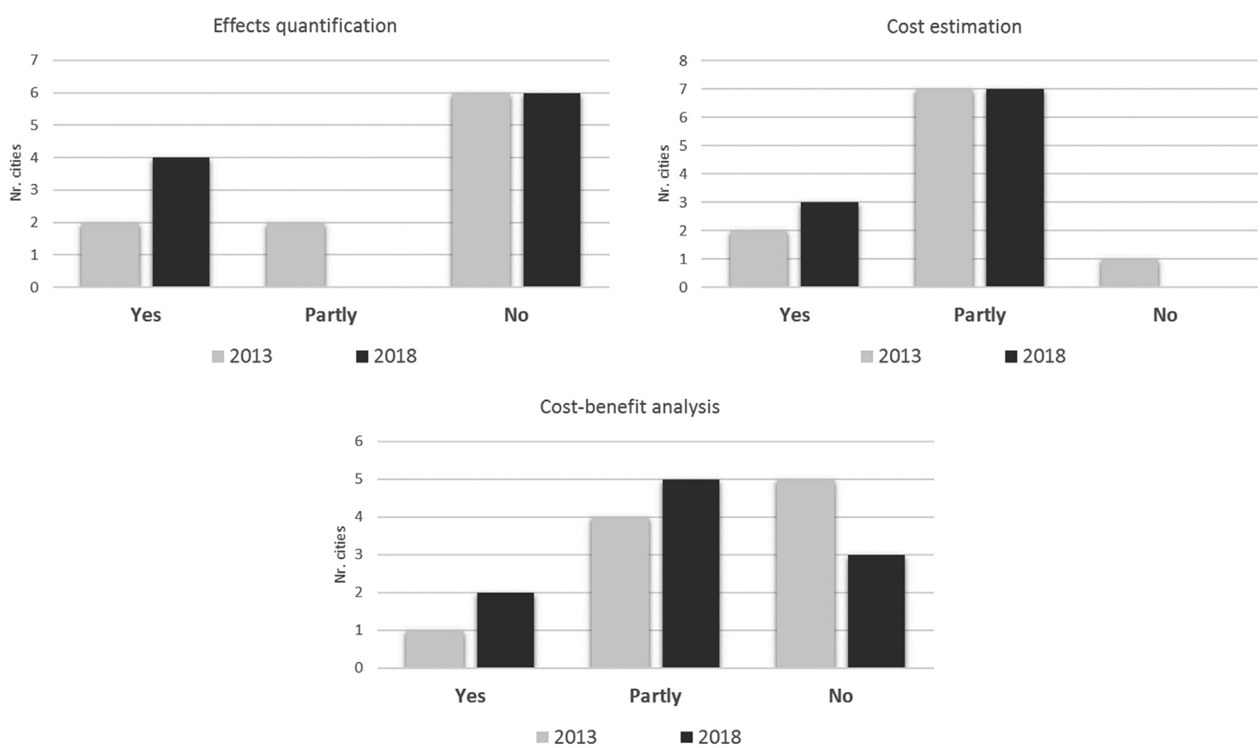

Fig. 2. Trend in implementation of tools to quantify the effects of measures (top left), to estimate costs (top right), and cost-benefit analyses (bottom), in 2013 and 2018 and for the 10 cities participating in both pilots (Antwerp, Berlin, Dublin, Madrid, Malmö, Milan, Paris, Plovdiv, Prague, and Vienna).

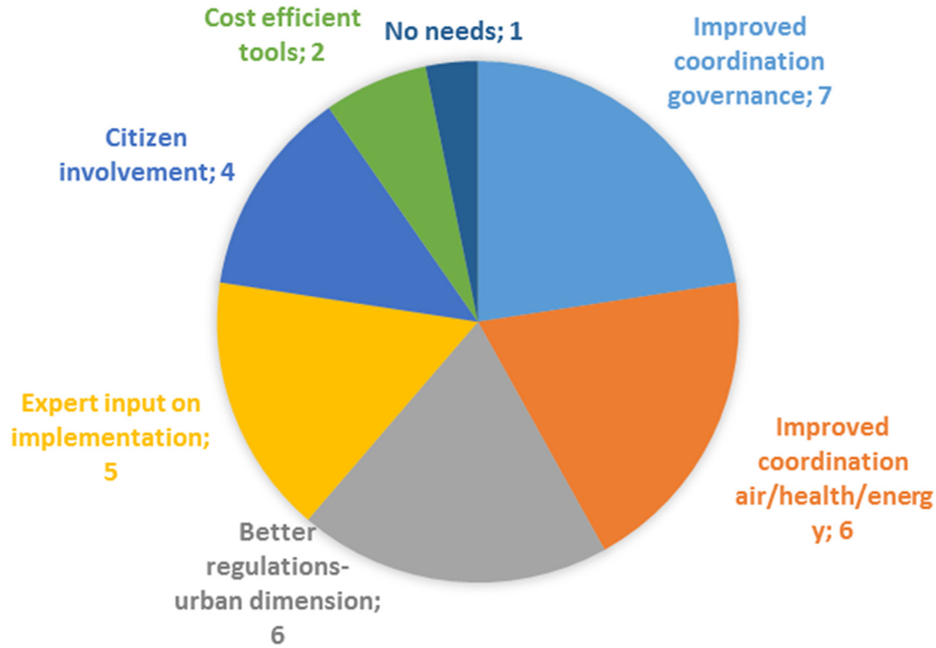

Fig. 4. Needs reported by the cities, and the number of cities reporting each of them.

also requested knowledge sharing and guidance regarding best practices and effective *vs*. non-effective measures. Specific examples shared in 2018 were city greening strategies (e.g., guidance on specific plant species to reduce ozone precursors; reported by Antwerp, Madrid and Prague), and TiO_2-related solutions. A dedicated forum for exchange of success and failure case studies, especially targeted towards cities and municipalities, would be largely beneficial according to the cities (reported in 2018).

In sum, city needs continued to be diverse and varied from one to another as evidenced in Fig. 4, which shows that there is no single "one size fits all" solution for AQ improvement. Specific needs from the cities, from both pilot years, were mainly improved collaboration between different administrative levels as well as with other sectors (climate, energy, noise), better regulation for the urban dimension, and the availability of expert input for the selection and implementation of mitigation measures. For the latter, the creation of a joint platform for AQ managers was proposed in 2018. Additionally, guidance on citizen involvement and cost-effective tools for AQ management, requested during both pilots, would guide the path towards healthier AQ.

3.3. General needs and challenges towards the future

Overall, a number of common needs were identified recurrently for all of the cities in 2013 and 2018:

- *Quantification of the effectiveness of mitigation strategies*: guidance on reliable, comparable and easy to use methodologies was requested. Co-benefits of mitigation strategies should be taken into account during the quantification of the effectiveness of mitigation measures. The implementation of mitigation strategies was driven by EU regulation (i.e., meeting of AQ limit values) as well as by public health concerns (i.e., the aim to go beyond EU limit values to pursue WHO guidelines).
- *Promotion of co-benefits*: AQ is only one component of urban well-being, along with other aspects such as noise, climate change, green spaces, etc. The active search and implementation of actions with known co-benefits, in a cross-sectoral approach, should boost the effectiveness of mitigation strategies and produce desirable synergistic effects. One example reported by Berlin was the speed limitation at 30 km/h, with co-benefits in terms of noise, road safety and AQ.
- *Cost-benefit analysis tools*: the cities recognised the usefulness of this kind of tools at the science-policy interface, to improve the communication of the benefits of AQ mitigation measures to the public and policy-makers. The limited application of these tools is mainly due, at present, to the lack of easy to use, comparable and reliable methodologies.
- *Communication strategies*: AQ specialists in the cities need clear and specific guidance on communication, possibly through external expert support, and in sharing of best practices and success stories. Guidance was requested in general, and specifically to deal with the rise of low-cost sensing technologies (e.g., EEA, 2019c).

In addition, two issues were highlighted in 2018:

- *Real-world, road vehicle emissions*: despite recurring reviews of vehicular emissions and emission standards, reliable, real-world data on emission types (e.g. EURO standards) which can be trusted for the design of low emission zones and traffic bans was not available to AQ managers in 2018. This is also applicable to data on alternative fuels such as LNG for trucks, or on the efficiency and emissions of natural gas light-duty vehicles. The data available on emission factors are numerous and arising from different sources, which are frequently conflicting or not communicated in an accessible way to AQ managers. This was a major challenge requiring detailed technical guidance.
- *Support from regional/national authorities for AQ improvements beyond the EU limit values*: a number of cities expressed their ambition to aim for WHO guideline values, and to achieve AQ improvements below EU limit values, once these are attained. However, this ambition was challenged by the lack of support from regional/national authorities.

4. Conclusions

Air quality managers from 12 and 10 European cities reported their views on urban AQ in their cities in two different time points by means of questionnaires distributed by the European Environment Agency and face-to-face meetings. The analysis presented in this work refers to trends and challenges in AQ mitigation strategies, and it does not aim to report air pollution concentration trends. The results show that, in 2018, several (though not all) of the cities had the ambition to continue decreasing air pollution concentrations to meet the WHO guidelines, once they were close to attainment of the EU limit values. The cities which did not yet have this ambition and aimed for the EU limit values did not have as much public awareness and support for AQ policies, which were considered key drivers in the cities targeting WHO guidelines. This novel development with regard to 2013 highlights the interest of AQ managers in reducing public health impacts from air pollution, going one step beyond compliance with EU limit values. However, this ambition in some of the cities is currently frustrated by legislation and objectives at regional and national levels, which target only the EU limit values. Actions at city-scale have high potential for AQ improvement and behavioural change, but must be supported through cooperation at regional, national and EU level. The cities acknowledged that AQ improvements at urban scale cannot be achieved with urban-scale actions only, which must be underpinned by air pollution reductions at regional scale. Counting on the support of administrations at different levels as well as on inspiration from other cities (e.g., by means of a common platform) would contribute to the overall improvement of urban AQ across Europe. The role of cities as net exporters of air pollution should also be acknowledged, and cooperation between them, enhanced. Relevant drivers of change, according to AQ managers, are economic incentives (as well as environmental benefits), and involving the local administrations and policy-makers early in the AQ management process.

The above issues seem to indicate that governance systems for AQ are not always optimised to support collaboration across administrative levels and thus maximise the effect of measures each level is implementing (which sometimes are even seen as contradictory). Especially subsidiarity between national, regional (if applicable) and local levels seems to be a problem often encountered by the city administrations.

The exchange of specific, experience-based results from successful and unsuccessful AQ improvement strategies was appreciated, for example in the form of a joint exchange platform for AQ experts for urban-scale study results. This kind of exchange would facilitate identifying emerging pollution sources such as inland shipping, wood burning, or construction/demolition works, as well as successful and unsuccessful abatement measures.

Finally, a systemic thinking approach to the future of AQ management was proposed: whether aiming for behavioural change regarding urban mobility, assessing the future of low emission zones in view of decreasing on-road emissions, or discussing the most adequate air pollution metrics to be monitored to establish links with health. Integrated approaches actively engaging administrations and the public, addressing co-benefits, and targeting specific pollutant sources, would constitute the roadmap leading to improved AQ in European cities. Extrapolating the findings from the 12 cities assessed to other major and medium-sized cities across Europe could maximise the potential of this approach.

CRediT authorship contribution statement

M. Viana: Conceptualization, Formal analysis, Methodology, Writing - original draft. **F. Leeuw:** . **A. Bartonova:** . **N. Castell:** . **E. Ozturk:** . **A. González Ortiz:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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