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Applying air pollution modelling within a multi-criteria decision analysis framework to evaluate UK air quality policies

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HIGHLIGHTS

- A modelling framework for evaluating UK air quality policies has been developed.
- The framework combines decision analysis, air pollution and impact modelling.
- Multi-criteria decision analysis is used for comparative evaluation of policies.
- The framework is used to evaluate idealized UK air quality policies.

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ABSTRACT

A decision support system for evaluating UK air quality policies is presented. It combines the output from a chemistry transport model, a health impact model and other impact models within a multi-criteria decision analysis (MCDA) framework. As a proof-of-concept, the MCDA framework is used to evaluate and compare idealized emission reduction policies in four sectors (combustion in energy and transformation industries, non-industrial combustion plants, road transport and agriculture) and across six outcomes or criteria (mortality, health inequality, greenhouse gas emissions, biodiversity, crop yield and air quality legal compliance). To illustrate a realistic use of the MCDA framework, the relative importance of the criteria were elicited from a number of stakeholders acting as proxy policy makers. In the prototype decision problem, we show that reducing emissions from industrial combustion (followed very closely by road transport and agriculture) is more advantageous than equivalent reductions from the other sectors when all the criteria are taken into account. Extensions of the MCDA framework to support policy makers in practice are discussed.

1. Introduction

Atmospheric chemistry-transport models have been used in various ways to evaluate air quality policies. They have been used mainly as either stand-alone simulation models (Chemel et al., 2014) or embedded within comprehensive integrated assessment tools (Lim et al., 2005; Amann et al., 2011; Thunis et al., 2012; Carnevale et al., 2012a, 2012b; Oxley et al., 2013). However, if air pollution modelling is to be used in practice to help policy makers choose amongst potentially competing policies, appropriate methods for comparative evaluation of such policies are needed (Browne and Ryan, 2011). Such methods include cost-effectiveness analysis (CEA), cost-benefit analysis (CBA) and multi-criteria decision analysis (MCDA).

CEA is mainly used when the policies are assessed against two criteria: monetary (e.g. cost of the policy) and non-monetary (e.g. effectiveness or benefit of the policy such as health gain). A cost-

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effectiveness ratio (cost per unit gain) is calculated for each policy and is used as the metric for comparative evaluation; the policy with the lowest ratio is deemed to be the most cost-effective. CBA is similar to CEA except that the non-monetary criterion is monetised and the ratio of cost to benefit becomes dimensionless, which eases comparison. CBA can cater for more than two criteria because all the non-monetary criteria are monetised. MCDA is different from CEA and CBA in one important aspect: the comparative evaluation between policies is carried out across several criteria without the need to monetise the criteria i.e., the criteria are maintained in their natural units. Browne and Ryan (2011) and Scrieciu et al. (2014) discuss the advantages and disadvantages of the different methods.

The use of MCDA to support environmental decision making has solid foundation (Kiker et al., 2005; Zhou et al., 2006). It has been recommended for this purpose by some UK Government Departments (DCLG, 2009). Huang et al. (2011) provide a review of the applications of MCDA in environmental sciences. The applications of MCDA of relevance to this study include evaluation of flood risk management policy options in Scotland (Kenyon, 2007), air quality policies in the UK (Philips and Stock, 2003; Fisher, 2006), and climate change mitigation and adaptation policies (Konidari and Mavrakis, 2007; Scrieciu et al., 2014; Chalabi and Kovats, 2014). Apart from the flood risk management MCDA study, the above-mentioned studies describe MCDA frameworks rather than evaluate specific polices.

The aim of this study is to demonstrate the use of an air pollution model alongside impact models within a MCDA framework to evaluate and compare relatively simple UK air quality policies across several criteria which include health and health inequality. We used the EMEP4UK chemical transport model (Vieno et al., 2010, 2014) to simulate air pollution over the UK for 2010. Results from an earlier version of the model have been used for health impact estimation (Doherty et al., 2009; Vardoulakis and Heaviside, 2012; Heal et al., 2013).

The paper is structured as follows. Section 2 describes the methods used in this study. Section 3 gives the results of the MCDA analysis. Section 4 highlights the main findings and discusses the merits and challenges of this approach in theory and practice, and the final section concludes. The paper is supported by five technical appendices.

2. Methods

2.1. Multi-Criteria Decision Analysis (MCDA)

Several MCDA methods with varying degrees of complexity could be used to carry out comparative evaluation of air quality policies. Exposition of MCDA methods are given by Belton and Stewart (2002) and Figueira et al. (2005). The method we used in this study belongs to the family of Simple Multi-Attribute Rating Techniques (SMART) and is also known as the weighted-sum method (Cunich et al., 2011; Dowie et al., 2013). We used the SMART software tool *Annalisa* (©Maldaba Ltd, http://maldaba.co.uk/products/annalisa) for implementing the MCDA. *Annalisa* has been used as a decision support framework for risk prioritisation of environmental health hazards (Woods et al., 2016).

The elements of this MCDA method are: (i) a set of policies, (ii) a set of criteria against which the policies are evaluated and compared, (iii) a set of preference weights which give the relative importance of each criterion (the weights add up to 1), (iv) a set of models to determine the impact of each policy on each criterion (each impact is normalised between 0 and 1), and (v) a method for integrating the impacts and the weights to give a total impact for each policy across all the criteria. The total impacts of all the policies are the metrics which are used to compare the policies. If the impacts are burdens then the policy with the lowest total impact is deemed to be the "optimal policy". Conversely, if the impacts are benefits then the policy with the highest total impact is the "optimal policy".

The theoretical details of the MCDA method are provided in Supplementary Material A to E. In summary, Supplementary Material A describes the stakeholder survey used to rank the criteria (described in Section 2.4: mortality, health inequality, greenhouse gas emissions, air quality legal compliance, biodiversity, crop yield) in order of their importance. Supplementary Material B describes the method of converting the ranks obtained from the stakeholders to a set of aggregated weights for the criteria. Supplementary Material C shows the method of normalising the impacts across the criteria to make them dimensionless. Supplementary Material D provides details on the measurement of pollution exceedance. Finally, Supplementary Material E describes the MCDA calculation.

2.2. Air pollution modelling

For the purposes of this study, pollutant concentrations of nitrogen dioxide (NO_2), ozone (O_3) and particulate matter with aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) were simulated by the EMEP4UK atmospheric chemistry transport model. EMEP4UK is a nested regional application of the main European Monitoring and Evaluation Programme (EMEP) MSC-W chemical transport model (Simpson et al., 2012) targeted specifically at air quality in the UK. EMEP4UK uses one way nesting to scale down from 50 × 50 km horizontal resolution in the EMEP greater European domain to 5 × 5 km resolution in a nested inner domain located over the British Isles. Model outputs include surface concentrations of gaseous pollutants and particulate matter (both primary and secondary) along with their rates of wet and dry deposition. The driving meteorology for EMEP4UK was taken from the Weather Research and Forecasting (WRF) model including data assimilation of 6-hourly meteorological reanalyses from the US National Center for Environmental Prediction (NCEP) global forecast system. Continuously constraining the WRF fields to observations ensures that the meteorology supplied to the chemistry-transport model is closely representative of the real weather conditions prevailing throughout the simulations. Full details of the WRF-EMEP4UK coupled model are described elsewhere (Vieno et al., 2010, 2014).

2.3. Policies

In this study we assess relatively simple policies that would reduce UK emissions from specific sectors by fixed fractions. We use the Selected Nomenclature for Air Pollution (SNAP) emission sectors, as defined by the EMEP CEIP (Center on Emissions Inventories and Projections: www.ceip.at). In particular, we evaluate policies that control emissions from the following sectors: SNAP 1. 'Combustion in energy and transformation industries'; SNAP 2. 'Non-industrial combustion plants'; SNAP 7. 'Road Transport'; and SNAP 10. 'Agriculture'.

2.3.1. Base simulation

The base simulation was for 2010. It used anthropogenic emissions of primary pollutants and pollutant precursors as reported in official inventories for that year. Annual gridded emissions of nitrogen oxides ($NOx = NO + NO_2$), sulphur dioxide (SO_2), ammonia (NH_3), Volatile Organic Compounds (VOCs), carbon monoxide, and particulate matter (PM_{10} and $PM_{2.5}$) were taken from the National Atmospheric Emissions Inventory (NAEI, http://naei.defra.gov.uk) for the UK and from CEIP for the rest of Europe. The provided anthropogenic emissions for each species are apportioned across a