**SUPPLEMENTARY MATERIAL**

# Applying Air Pollution Modelling within a Multi-Criteria Decision Analysis Framework to Evaluate UK Air Quality Policies

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**A. Rank survey**

Please:

- Put rank 1 against the criterion you consider to be the most important,
- Put rank 2 against the criterion you consider to be the second most important
- ……
- Put rank 6 against the criterion you consider to be the least important:

| *Criterion* | *Rank* |
|---|---|
| Mortality (human health) | |
| Health inequality (social) | |
| Greenhouse emissions (climate) | |
| Pollution exceedance (legal compliance) | |
| Biodiversity (ecosystem health) | |
| Crop yield (ecosystem health) | |

All the criteria should be ranked. Each criterion should have a unique rank. The ranks will not be attributed to you personally but will be used in the MCDA analysis.

To assist you make your decision we provide below a description of the quantitative measures used for each criterion along with a short description. Each measure applies only to emissions from/impacts within the UK.

| *Criterion* | *Quantitative measure* | *Description* |
|---|---|---|
| Mortality | Years of life lost (YLL) | Years of life lost (or gained) associated with $PM_{2.5}$ exposure summed over the whole population |
| Health inequality | Socio-economic gradient in health | Change in YLL per 10th – 90th centile of deprivation score |
| Greenhouse gas emissions | $CO_2$-equivalent emissions (kg $CO_2$ eq) | These are based on the 'Kyoto' basket of gases associated with each sector. |
| Pollution exceedance | Number of 5 km grids for which $NO_2$, $O_3$ and $PM_{2.5}$ exceed their permitted levels | Use EC air quality standards |
| Biodiversity | N-deposition flux (kg-N $m^{-2}$ $y^{-1}$) | Enhanced nitrogen deposition tends to increase the exposure of ecosystems to acidity and also tends to reduce biodiversity. |
| Crop yield | $O_3$ deposition flux (kg-$O_3$ $m^{-2}$ $y^{-1}$) | Because ozone is a strong oxidant, it can cause significant damage to some plants, including major UK crops such as wheat, reducing yields. |

**B. Converting ranks to aggregate weights**

This section outlines the method used for determining aggregate weights from the ranks provided by stakeholders. Each stakeholder was asked to rank the 6 criteria in terms of their importance where rank 1 means that it is the most important criterion and rank 6 means that it is the least important criterion. The matrix below illustrates the ranks provided by two stakeholders:

| | *Ranks →* | | | | | |
|---|---|---|---|---|---|---|
| *Stakeholders↓* | 1 | 2 | 3 | 4 | 5 | 6 |
| $S_1$ | $C_3$ | $C_5$ | $C_6$ | $C_4$ | $C_1$ | $C_2$ |
| $S_2$ | $C_2$ | $C_1$ | $C_4$ | $C_6$ | $C_3$ | $C_5$ |

In this matrix, $S_1$ and $S_2$ are the two stakeholders and $C_1$ to $C_6$ are the six criteria. In this example, stakeholder $S_1$ ranked the criteria in the following order: $C_3$ (most important), $C_5$, $C_6$ $C_4$, $C_1$, $C_2$ (least important); whereas stakeholder $S_2$ ranked them in the following order: $C_2$ (most important), $C_1$, $C_4$, $C_6$, $C_3$, $C_5$ (least important).

Each set of ranks provided by a stakeholder is converted first to weights such that for $m$ criteria, (i) the weights add up to unity, and (ii) the weight of the criterion of rank 1 > weight of the criterion of rank 2 > weight of the criterion of rank 3> …..> weight of the criterion of rank $m$. There are several methods of carrying out this conversion and these differ in how steep they make the weights across the ranks (Stillwell et al 1981, Jia et al 1998, Kenyon 2007). For example the rank-order centroid (ROC) weights method concentrates the weights in the first few criteria. We used the rank sum (RS) weights method which provides in general a less steep pattern than the ROC and other methods.

The RS weights method is explained as follows: if $i_j$ is the rank of criterion $C_j$, then its weight $w_j$ is given by the following equation:

$$w_j = \frac{m + 1 - i_j}{\sum_{k=1}^{m} k} \qquad (B.1)$$

where $m$ is the total number of criteria. In this method each criteria is weighted in proportion to its position in the rank order. The denominator in Equation (B.1) is the sum of the ranks and the numerator is the reverse rank of the criterion.

Equation (B.1) simplifies to:

$$w_j = \frac{m + 1 - i_j}{\sum_{k=1}^{m} k} = \frac{2(m + 1 - i_j)}{m(m + 1)} \qquad (B.2)$$

It can be shown that

$$0 \leq w_j \leq 1 \qquad (B.3)$$

and

$$\sum_{j=1}^{m} w_j = 1 \qquad (B.4)$$

For example, the relative weights of the criteria ranked by stakeholder $S_1$ (using Equation (B.2)) is

| *Criterion* | $C_3$ | $C_5$ | $C_6$ | $C_4$ | $C_1$ | $C_2$ |
|---|---|---|---|---|---|---|
| *Rank* | 1 | 2 | 3 | 4 | 5 | 6 |
| *Weight* | 0.2857 | 0.2381 | 0.1905 | 0.1429 | 0.0952 | 0.0476 |

The weights add to 1. In general, the aggregate weight of criterion $C_j$ (where $j = 1..m$) pooled across $N$ stakeholders is given by:

$$\hat{w}_j = \frac{1}{N}\sum_{i=1}^{m} n_{i,j} w_{i,m} \qquad (B.5)$$

where $N$ is the total number of stakeholders, $n_{i,j}$ is the number of stakeholders who selected rank $i$ for criterion $C_j$ and $w_{i,m}$ is the weight associated with rank $i$ for a set of $m$ criteria.

For example, if three stakeholders gave the following ranks for the above 6 criteria:

| | |
|---|---|
| $S_1$ | $C_3$ (most important), $C_5$, $C_6$, $C_4$, $C_1$, $C_2$ (least important) |
| $S_2$ | $C_2$ (most important), $C_4$, $C_1$, $C_6$, $C_3$, $C_5$ (least important) |
| $S_3$ | $C_2$ (most important), $C_1$, $C_3$, $C_4$, $C_6$, $C_5$ (least important) |

then using Equation (B.5), the aggregate weights for each of the criteria pooled across the three stakeholders are:

| *Criterion* | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ |
|---|---|---|---|---|---|---|
| *Aggregate weight* | 0.1746 | 0.2063 | 0.1905 | 0.1746 | 0.1111 | 0.1429 |

The total aggregate weights also add up to 1.

## C. Normalisation of impacts

This section describes a method to transform the impacts on the criteria (which naturally are in different units) into a dimensionless unit for use in the MCDA. We require all the impacts to be pointing in the same direction i.e. the objective is either to increase the impacts (i.e. higher impacts are more beneficial) or to decrease them (i.e. lower impacts mean more beneficial). In this application, the objective is to decrease all the impacts (YLLs, socio-economic gradient, kg $CO_2$ eq, pollution exceedance, kg-N $m^{-2}$ $y^{-1}$, kg-$O_3$ $m^{-2}$ $y^{-1}$).

Assume we have $n$ policies $P_1 \dots P_n$ to evaluate and denote the impact of policy $P_i$ on criterion $C_k$ by $x_{ik}$. If the impacts on the criterion are strictly positive (e.g. kg-N $m^{-2}$ $y^{-1}$), we use a two-step normalisation procedure to transform the impacts into a dimensionless quantity between zero and 1 as follows. For each criterion $C_k$ calculate the highest impact over all the policies i.e.

$$y_k^* = \max_{P_i} x_{ik} \qquad (C.1)$$

The normalised impact for any policy $P_i$ on criterion $C_k$ is then given by:

$$\hat{x}_{ik} = {}^{x_{ik}}/_{y_k^*} \qquad (C.2)$$

If the impact of a policy on a criterion can be positive or negative (e.g. YLLs), then we applied the following normalisation procedure: shift all the impacts to positive values by adding the modulus of the highest negative impact to all impacts before normalising so that the lowest detrimental impact is zero

## D. Measuring legal compliance

This section describes a measure of legal compliance. It is the number of spatial grids for which the legislative threshold of each pollutant is exceeded, summed over the two pollutants. Because the threshold legal level for $PM_{2.5}$ is based on yearly values and for ozone on daily values, the number of threshold exceedence for ozone is weighted accordingly before summing the number of exceedences over the pollutants.

Denote (i) each 5 km grid by the variable $k$ where $k = 1..n$ and $n$ is the total number of grids, (ii) the annual concentration of $PM_{2.5}$ (μg $m^{-3}$) for grid $k$ by $z_{k,PM_{2.5}}$, and (iii) the maximum daily 8 hour mean of $O_3$ (μg $m^{-3}$) for grid $k$ and day $t$ by $z_{k,t,O_3}$ where $t = 1..365$. For $PM_{2.5}$ count the number of grids for which the annual average exceeds the limit i.e.

$$\Phi_{PM_{2.5}} = \sum_{k=1}^{n} I\left(z_{k,PM_{2.5}} > 25\right) \qquad (D.1)$$

where $I(S)$ is the indicator function of set (i.e. $I(S) = 1\ if\ S$ is true and zero if it is false).

For $O_3$ count the number of grids for which maximum daily 8 hour mean of $O_3$ exceeds the limit over one year:

$$\Phi_{O_3} = \sum_{t=1}^{365} \sum_{z=1}^{n} I\left(z_{k,t,O_3} > 120\right) \qquad (D.2)$$

Exceedance is defined as:

$$\mathrm{E} = \Phi_{PM_{2.5}} + \frac{1}{365}\Phi_{O_3} \qquad (D.3)$$

**E. MCDA Calculation**

This section outlines the key MCDA calculation (Equation (E.1) below). Denote (i) the $n$ policies by $P_i, i = 1..n$, the $m$ criteria $C_j, j = 1..m$, (ii) the aggregated weights by $\omega_j, j = 1..m$ , and (iii) the impacts by $x_{ij}, i = 1..n, j = 1..m$ where $x_{ij}$ is the normalised impact of policy $P_i$ on criterion $C_j$.

The integrated score $S_i$ of a policy $P_i$ across all criteria is given by

$$S_i = \sum_{j=1}^{m} w_j \times x_{ij} \qquad i = 1..n \qquad (E.1)$$

Equation (E.1) simply says that the integrated score of each policy across all criteria is the weighted sum of the normalised impacts of the criteria. The policy with the lowest score is the 'optimal' policy which has the least detrimental impact.

**References**

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