InterCriteria Analysis Applied on Air Pollution Influence on Morbidity

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Abstract: Human health is reflected in all spheres of life and the economy. One of the main causes of morbidity and early mortality is polluted air. Ambient air pollution is a serious source of disease and mortality across the world. Cities are notorious for their high levels of air pollution and sickness. However, the precise degree of the health impacts of air pollution at the municipal level are still largely unclear. One of the main reasons for increased morbidity is the presence of particulate matter. The aim of our study is to show the relationship between elevated levels of particulate matter in the air and certain diseases. In this paper, we apply InterCriteria Analysis (ICrA) to find the correlation between the level of air pollution and the number of people seeking medical help. This is a new approach for the problem. The results show the affect of air pollution on certain diseases with a short exposure on polluted air and when the exposure is prolonged. We observed that some diseases are exacerbated by brief exposure to polluted air, while in others, exacerbation occurs after prolonged exposure.

Keywords: InterCriteria analysis; air pollution; particulate matter

1. Introduction

Exposure to outdoor air pollution has been linked to a variety of health problems in humans [1]. Many pieces of research have repeatedly and convincingly demonstrated relationships between urban Air Pollution (AP) and human health [2,3], particularly for short-term impacts, such as cardiovascular events [4], neurovascular events [5,6] and asthma [7]. The cost of human life is high, with current revised modeling estimating that AP causes about 9 million fatalities each year [8]. Around 25% of early fatalities linked to AP are caused by respiratory problems [9]. Short-term exposure to air pollution has serious impacts on asthma sufferers [10]. A large body of evidence from epidemiologic research implies a link between acute morbidity and exposure to particulate matter (PM) pollution [11].

The majority of this information comes from time series analysis [12] that compares hospitalization fluctuations to average particulate matter variations [13]. PM causes airway inflammations [14], and because the respiratory system is a frequent entry point, limiting airway exposure reduces the cardiovascular consequences [15–17]. Multicity studies exist as well, such as the European Air Pollution and Health: a European Approach (APHEA) project [18] and the American National Morbidity, Mortality and Air Pollution Study (NMMAPS) [19], both of which provide consistent evidence for the link between health and air pollutants for multiple cities over a large geographic area. The effects of air pollution can be viewed as an increase in a person’s risk of disease or injury, or as an extra danger to a population’s overall well-being. [20].
In [21,22], the authors proposed an air pollution model based on the Monte Carlo method and sensitivity analysis. The goal of their model was air quality management for reducing or eliminating the negative effects of air pollution on public health. As a result, it is critical to identify “adverse” effects and separate them from “non-adverse” ones, so that protection efforts may be focused on the pollutants that have the most severe health consequences.

InterCriteria analysis (ICrA) is a new approach, close to the correlation analysis, including a level of uncertainty, and thus it is more close to the real life [23]. In our research, we applied ICrA to evaluate the correlation between the air pollution and considered diseases. As data, we used the norms of the World Health Organization (WHO) for pollution and the number of people seeking medical help.

ICrA is based mainly on two formalisms: the processing of data by index matrices and intuitionistic fuzzy sets including uncertainty. The idea of ICrA is to manage problems where measuring the objects is slow, expensive and subjective [24]. The ICrA approach has been applied for a large area of problems, and the applicability of the ICrA and its correctness were approved in the published results [24–26]. More information about the theoretical aspects and application on ICrA can be found on the Inter Criteria Analysis Portal (https://intercriteria.net/ (accessed on 18 February 2022)).

The rest of the paper is organized as follows. In Section 2, guidelines of air quality are detailed. Section 3 provides some theoretical description of ICrA. Our computational results, analysis and discussion are presented in Section 4. Finally, Section 5 gives our concluding remarks and directions for future work.

2. The Air Quality Limits

It is now widely acknowledged that PM, nitrogen dioxide and ozone near the earth’s surface are the three pollutants that cause most morbidity and deaths in cities. In this paper, we focus on PM of size 10 µm (PM$_{10}$) and 2.5 µm (PM$_{2.5}$). For the purposes of the research, we will accept that, above certain limits, air quality is considered as dangerous and below these limits, as healthy [27].

The Air Quality Guidelines (AQGs) were proposed by the World Health Organization (WHO) (https://apps.who.int/iris/handle/10665/345329 (accessed on 20 February 2022)). These determine the levels of air quality required to preserve human health across the world based on significant scientific research. The guideline levels can be used as an evidence-based reference and an instrument to develop effective actions to reduce air pollution and thereby safeguard human health.

Table 1 shows the recommended level of particulate matter according to the World Health Organization and permissible level of particulate matter according to the EU Air Quality Directive. We can see the differences between the legislation and recommendations. The World Health Organization (WHO) guidelines are limits that aim to preserve human health across the world, based on significant scientific research. They are more like recommendations than rules—they are not obligatory. On the other hand, the EU Air Quality Directive (https://ec.europa.eu/environment/air/quality/existing-leg.htm (accessed on 20 February 2022)) is a legislation that must be followed by all EU member states. The EU Directive aims to preserve human health from air pollution but also takes political and economic factors into account.

| Air Pollution Norms | WHO AQGs (2005) | EU Directives |
|---------------------|----------------|--------------|
|                     | PM$_{10}$ | PM$_{2.5}$ | PM$_{10}$ | PM$_{2.5}$ |
| daily               | 50       | 25         | 50       | -          |
| yearly              | 20       | 10         | 40       | 25         |
The most notable distinction is that the EU Air Quality Directive does not include a daily limit for PM$_{2.5}$, which is considered as the deadliest air pollutant in cities worldwide [27]. The EU directive is also less restrictive in terms of yearly limits for both PM$_{2.5}$ and PM$_{10}$, whereas both the EU directive and WHO standards limit PM$_{10}$ to 50 g/m$^3$ daily. We decided to use the WHO standards for this study since they are recommended globally, and they have a daily limit for PM$_{2.5}$.

At the time of writing this paper, the WHO has issued new AQGs for the first time after 16 years, and they are more strict compared to the previous proceedings as can be seen in Table 2. The most significant differences between the two WHO guidelines are the levels of particulate matter under 2.5 microns (PM$_{2.5}$) and nitrogen dioxide (NO$_2$). The new annual guideline for PM$_{2.5}$ is two-times stricter than the old guidelines, changed from 10 to 5 µg/m$^3$, and the daily guideline was changed from 25 to 15 µg/m$^3$.

Table 2. Air quality: WHO guidelines 2005 and 2021.

| Air Pollution Norms | WHO AQGs (2005) | WHO AQGs (2021) |
|---------------------|-----------------|-----------------|
| PM$_{10}$ daily     | 50              | 25              |
| PM$_{2.5}$ daily    | 25              | 15              |
| PM$_{10}$ yearly    | 20              | 15              |
| PM$_{2.5}$ yearly   | 10              | 5               |

In the last decade, there has been a significant increase in evidence demonstrating how air pollution impacts several areas of health. As a result, and following a thorough assessment of the available data, the WHO lowered virtually all AQGs levels from 2005, warning that exceeding the new air quality guideline limits has considerable health risks. Adherence to them, on the other hand, might save millions of lives. According the WHO, around 80% of fatalities worldwide attributable to PM$_{2.5}$ exposure might be prevented if countries met the NEW annual PM$_{2.5}$ AQG threshold of 5 µg/m$^3$ [27]. Reaching the interim goals will also have significant health advantages. In the case of PM$_{2.5}$, achieving intermediate goal 4 (the same level as the AQG from 2005 = 10 µg/m$^3$) would result in a roughly 48% reduction in overall fatalities due to PM$_{2.5}$ exposure [27].

3. InterCriteria Analysis

ICrA is a variant of correlation analysis with an included level of uncertainty. It is based on index matrices (IM) [28–32] and intuitionistic fuzzy sets (IFSs) [33–35]. The main idea is presented briefly. More theoretical details can be found in [23] and on the InterCriteria Analysis Portal (https://intercriteria.net/ (accessed on 20 February 2022)).

An ordered pair of real non-negative numbers $(a, b)$, where $a, b \in [0, 1]$ and $a + b \leq 1$, is called an intuitionistic fuzzy pair (IFP) [24]. The components $a$ and $b$ can be interpreted as a degree of “membership” and “non-membership” to some set, a degree of “validity” and “non-validity”, a degree of “agreement” and “disagreement”, etc. In 1987, Atanasov proposed index matrices [28], and more details and discussions can be found in [29,30]. For the ICrA application, the initial index set consists of criteria (rows) and objects (columns) and elements, which are IFP and determine the degree of correlations between criteria.

Let the set of $n$ objects, which will be evaluated, be denoted by $O$ and the set of assigned values to the objects by $m$ criteria $C$ is denoted by $C(O), C = \hat{C}_p$ for a fixed $p$, i.e.,

$$O \equiv \{O_1, O_2, O_3, \ldots, O_n\},$$

$$C(O) \equiv \{C(O_1), C(O_2), C(O_3), \ldots, C(O_n)\}.$$  

If $x_i = C(O_i)$, we can define the following set:

$$C^*(O) \equiv \{(x_i, x_j)\mid i \neq j \& (x_i, x_j) \in C(O) \times C(O)\}.$$  

If $x = C(O_i)$ and $y = C(O_j)$ and $i < j$, then $x < y$. 

Further, to find the level of agreement of couples of the criteria, we constructed vectors of internal comparison for each criterion. The elements of the vectors belong to one of the three sets $R$, $\bar{R}$ and $\tilde{R}$, which are defined as follows: for any criterion $C$ and ordered pair $(x, y) \in C^*(O)$

$$\begin{align*}
(x, y) &\in R \iff (y, x) \in \bar{R}, \quad (1) \\
(x, y) &\in \bar{R} \iff (x, y) \notin (R \cup \bar{R}), \quad (2) \\
R \cup \bar{R} &\cup \tilde{R} = C^*(O). \quad (3)
\end{align*}$$

Thus, if $(x, y) \in R$ when $x < y$, then $(x, y) \in \bar{R}$ when $x > y$.

Let, for brevity, $C_{i,j} = \langle C(O_i), C(O_j) \rangle$. Then, for a fixed criterion $C$, the following vector is constructed:

$$V(C) = \{C_{1,2}, C_{1,3}, \ldots, C_{1,n}, C_{2,3}, \ldots, C_{2,n}, C_{3,4}, \ldots, C_{3,n}, \ldots, C_{n-1,n}\}.$$ 

The degree of “agreement” between two criteria is the number of identical elements of the corresponding vectors, normalized by their length. The number of elements of the vector $V(C)$ is $n(n-1)/2$.

For each $k$-th component $(1 \leq k \leq n(n-1)/2)$, it is true that:

$$\hat{V}(C) = \begin{cases} 
1 & \text{if } V_k(C) \in R, \\
-1 & \text{if } V_k(C) \in \bar{R}, \\
0 & \text{otherwise}.
\end{cases}$$

Then, when comparing two criteria, the degree of “agreement” between the two is the number of matching components (divided by the length of the vector for normalization purposes). The degree of “disagreement” is the number of components of opposing signs in the two vectors (again normalized by the length).

The above described algorithm for calculating the degrees of “agreement” ($\mu$) and degrees of “disagreement” ($\nu$) between two criteria $C$ and $C'$ is realized in MATLAB according to [36].

The difference

$$\pi_{C,C'} = 1 - \mu_{C,C'} - \nu_{C,C'} \quad (4)$$

is considered as a degree of “uncertainty”.

The following index matrix is constructed as a result of applying the ICrA:

|       | $C_2$ | $\ldots$ | $C_m$ |
|-------|-------|----------|-------|
| $C_1$ | $\langle \mu_{C_1,C_2}, \nu_{C_1,C_2} \rangle$ | $\ldots$ | $\langle \mu_{C_1,C_m}, \nu_{C_1,C_m} \rangle$ |
| $\vdots$ | $\vdots$ | $\ddots$ | $\vdots$ |
| $C_{m-1}$ | $\langle \mu_{C_{m-1},C_m}, \nu_{C_{m-1},C_m} \rangle$ | $\ldots$ | $\langle \mu_{C_{m-1},C_m}, \nu_{C_{m-1},C_m} \rangle$ |

which determines the degrees of correspondence between criteria $C_1, \ldots, C_m$.

4. Computational Results and Discussion

It is known that polluted air affects human health. The main focus of this paper is the relationship between air pollution and morbidity. We conducted a correlational analysis using the AQGs from 2005 and ran the same method and calculations with the latest limits from AQGs (2021). The days with excessive pollution increased when AQGs (2021) was applied, and the correlation level decreased especially when considered on a daily basis. Therefore, the reported results are according to the AQGs from 2005.

The used data are the air concentration of the particulate matter and number of people who sought medical help. The used data are from the Bulgarian capital Sofia for the period from January 2018 until March 2019. A period before the Corona virus pandemic was
chosen to rule out its impact. The diseases that we analyzed were diabetes, inflammation of
the ears (IE), heart problems (HP), respiratory diseases (RD), gastritis, hypertension (h-tens)
and asthma. In respiratory diseases, we included all respiratory problems without asthma.
We combined certain diseases because they related to each other. Two variants of analysis
were made: on a monthly basis and on a 3-day basis. This gives us a possibility to see
which diseases are influenced when a person is exposed to polluted air for a long time and
which are influenced when a person is exposed for only a short time.

The data are for the daily level of particulate matter for the specified period and the
daily number of the people with health problems for the same period. After consultation
with medics, a one-month basis and a three-day basis were selected for our calculations.

First, the average monthly level of particulate matter was calculated, and the people
with the above diseases were summed per month. ICrA was applied to these data with the
aim to see the relationship between monthly exposure to polluted air and the number of
people seeking medical help. A cross-platform software for the ICrA approach, ICrAData,
was used [37].

The results are presented as an IM. The analysis of the results was conducted based on
the proposed consonance and dissonance scale in [38] as presented in Table 3.

### Table 3. The consonance and dissonance scale.

| Interval of $\mu_{C,C'}$ | Meaning                |
|-------------------------|------------------------|
| [0.00–0.05]             | strong negative consonance |
| (0.05–0.15]             | negative consonance     |
| (0.15–0.25]             | weak negative consonance|
| (0.25–0.33]             | weak dissonance         |
| (0.33–0.43]             | dissonance              |
| (0.43–0.57]             | strong dissonance       |
| (0.57–0.67]             | dissonance              |
| (0.67–0.75]             | weak dissonance         |
| (0.75–0.85]             | weak positive consonance|
| (0.85–0.95]             | positive consonance     |
| (0.95–1.00]             | strong positive consonance|

In Table 4, the results of the “degree of agreement” $\mu$-values are listed.

### Table 4. ICrA results based on one month pollution exposure: $\mu$-values.

|          | PM | Diabetes | IE | HP | RD  | Gastritis | h-tens | Asthma |
|----------|----|----------|----|----|-----|-----------|--------|--------|
| PM       | 1  | 0.62     | 0.79| 0.58| 0.91| 0.68      | 0.65   | 0.79   |
| diabetes | 0.62| 1        | 0.77| 0.76| 0.65| 0.71      | 0.71   | 0.76   |
| IE       | 0.79| 0.77     | 1   | 0.80| 0.85| 0.71      | 0.77   | 0.88   |
| HP       | 0.58| 0.48     | 0.80| 1   | 0.74| 0.58      | 0.45   | 0.65   |
| RD       | 0.91| 0.65     | 0.85| 0.74| 1   | 0.65      | 0.68   | 0.79   |
| gastritis| 0.68| 0.71     | 0.71| 0.58| 0.65| 1         | 0.74   | 0.82   |
| h-tens   | 0.65| 0.71     | 0.77| 0.45| 0.68| 0.74      | 1      | 0.73   |
| asthma   | 0.79| 0.76     | 0.88| 0.65| 0.79| 0.82      | 0.73   | 1      |
The most important are the data from the first line (respectively column) of the table. These give the relation between the level of the pollution and diseases. In bold are diseases with a high correlation with pollution and in italics are diseases with a low correlation with pollution. Other diseases did not correlate with pollution. From Table 4, we see that inflammation of the ears, respiratory diseases and asthma had a high correlation with the level of air pollution.

This means that, with prolonged exposure to high levels of fine particulate matter, the likelihood of these diseases is high. The highest is the correlation concerning respiratory problems, which is not surprising. Diseases, such as diabetes, heart problems, gastritis and hypertension are less affected by pollution but still have an impact. Peoples with heart problems are not affected by one month’s exposure to air pollution. From Table 4, we see correlations between the considered diseases. We observed a high correlation between inflammation of the ears and heart problems ($\mu = 0.80$), respiratory diseases and asthma ($\mu = 0.79$) and gastritis and asthma ($\mu = 0.88$). There was a high correlation between heart problems and inflammation of the ears as well.

After ICrA was applied regarding the daily level of pollution and the sum of the people with diseases during the same day and the next three days. We assumed that when there is a day with an increased level of pollution, health problems can occur in the next few days, regardless of whether the level of pollution has decreased. The obtained results are presented in Table 5.

**Table 5.** ICrA results based on one day of pollution exposure: $\mu$-values.

|       | PM   | Diabetes | IE    | HP    | RD    | Gastritis | h-tens | Asthma |
|-------|------|----------|-------|-------|-------|-----------|--------|--------|
| PM    | 1    | 1        | 0.40  | 0.52  | 0.62  | 0.78      | 0.59   | 0.48   |
| diabetes | 1    | 1        | 0.46  | 0.48  | 0.61  | 0.63      | 0.56   | 0.44   |
| IE    | 0.40 | 0.46     | 1     | 0.48  | 0.54  | 0.46      | 0.58   | 0.49   |
| HP    | 0.52 | 0.48     | 0.48  | 1     | 0.58  | 0.57      | 0.54   | 0.50   |
| RD    | 0.62 | 0.61     | 0.54  | 0.58  | 1     | 0.65      | 0.60   | 0.47   |
| gastritis | 0.78 | 0.63     | 0.46  | 0.57  | 0.65  | 1         | 0.58   | 0.38   |
| h-tens | 0.59 | 0.56     | 0.58  | 0.54  | 0.60  | 0.58      | 1      | 0.48   |
| asthma | 0.48 | 0.44     | 0.49  | 0.50  | 0.47  | 0.38      | 0.48   | 1      |

The observation on a three-day basis is different. As can be seen from Table 5, between the air pollution (PM) and diabetes, the highest correlation was observed. A lower correlation between PM and gastritis was also observed. The correlation between air pollution and respiratory diseases was lower. No correlation was observed between air pollution and asthma and inflammation of the ears. This result can be explained by the fact that, when the pollution is short-term, for example only for one day, asthma will not be affected so much that patients seek medical help (the people who seek medical help are too few to affect the results).

From this study, we can conclude that some diseases are affected by air pollution even with a short exposure of one or several days, while other diseases occur when a person is exposed for a long time (for example, one month).

5. Conclusions

The aim of this paper was to study the influence of air pollution, specifically particulate matter, on human health. Seven diseases of great social significance were selected: diabetes, inflammation of the ears, heart problems, respiratory diseases, gastritis, hypertension and asthma. A period of one year and three months was chosen before the COVID-19 pandemic to rule out any impact of the disease. Two types of research were performed: the impact of
pollution on health when a person was exposed for a month and the impact of air pollution on health when pollution exposure was for a short term.

The results showed that air pollution affects certain diseases even with a short exposure to polluted air, while others have an effect when the exposure is prolonged. Diseases such as diabetes and gastritis were exacerbated by short-term exposure to polluted air, while diseases such as inflammation of the ears, the upper respiratory tract and asthma were exacerbated by prolonged exposure to polluted air.

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