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Use of measurement results from a mobile laboratory in the diagnostics of anthropogenic environment – linear ordering of objects using the TOPSIS method

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Abstract: The measurements of the concentrations of gaseous and dust pollutants in the anthropogenic environment are an important element of environmental monitoring and for determining directions of preventive activities in the field of health protection. The article presents the results involving the concentrations of suspended dust and gaseous pollutants in the outdoor air, which were recorded at three measuring stations of air quality in the Silesian and Opole voivodeships (Wodzisław Śląski, Zabrze, Kędzierzyn-Koźle). The results were supplemented with the values recorded by the mobile laboratory located at the Center for Continuing Education - Branch of the Silesian University of Technology in Rybnik. The research results were used for a synthetic assessment of the threat level to the anthropogenic environment. In the computational layer, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was employed, which is included in the group of methods for solving multi-criteria decision-making problems (*Multi Attribute Decision Making*).

Introduction

Large European cities are characterized by poor air quality, which is confirmed by reports demonstrating the areas of high concentrations of major pollutants, which often exceed the WHO (World Health Organization) guidelines (Machaczka et al. 2023, Yazdi et al. 2021). Most Europeans live in urban areas, so poor air quality has a negative impact on their health, including conditions such as the development of cardiovascular diseases, lung cancer and high human mortality ratio (WHO 2021, WHO 2022). Additionally, a significant association between air pollution and the development of obstructive lung diseases has been observed (Paplińska-Goryca et al. 2021). High levels of air pollution with PM_{10} and $PM_{2.5}$ dust or gaseous pollutants such as CO and NO_x in cities around the world, along with weather patterns and specific climatic conditions, have had a significant impact on the increase in COVID-19 rates and resulting deaths (Meo et al. 2022, Zoran et al. 2020, Juginović et al. 2021). Furthermore, research has shown a significant impact of air pollution on the growth and development processes of people, their general psychophysical condition, as well as the quality and length of human life (Lopuszanska-Dawid et al. 2020).

In Poland, the concentration of PM_{10} and $PM_{2.5}$ dust in the air of urban-industrial agglomerations reaches much higher levels than that in Western European countries. In Western European cities, transportation sources predominantly contribute to nitrogen oxide pollution. In Poland, significant issues arise from dust pollution and benzo(a)pyrene, primarily emitted by the municipal and domestic sectors. Additionally, gaseous pollutants such as nitrogen oxides (NO_x) emitted by road transport are significant contributors (Kaczmarczyk 2017).

Although air pollution concentrations, including $PM_{2.5}$, as well as the associated mortality and disease burden, have significantly decreased in Europe over the last three decades, almost 75% of Europeans still live in areas where air quality fails to meet WHO requirements (WHO 2021). Poland stands out as one of the European countries with the lowest air quality, which is also confirmed by current EEA reports (ISGlobal 2021, EEA 2022), documenting, among others, the dominant contribution of Polish cities in the pollution of Europe with suspended particulate matter.

Rybnik, located in southern Poland, grapples with persistent issue of air pollution, particularly exacerbated during winter periods. The combustion of coal, both in the municipal sector and through individual heating systems, significantly contributes to the deterioration of air quality in Rybnik. The intense and widespread burning of coal during colder months leads to heightened pollution emissions, especially from outdated heating installations.

To address and evaluate the complexity of air pollution, a multi-criteria assessment approach using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is employed. This method allows for effective comparisons between different areas, regions, or time periods regarding atmospheric pollutant levels and their impact on human health and the environment.

The article presents an example of the application of the TOPSIS method in the assessment of air pollution concentrations.

Materials & Methods

Materials

Location of measurement points

The article uses data from measurements of gas and dust pollutant concentrations in outdoor air. These measurements were conducted in February 2023 at various locations, including the temporary location of the mobile laboratory situated on the former campus of the Silesian University of Technology in Rybnik, at 54 Tadeusza Kościuszki Street (Fig. 1). Additionally, measurements were taken at monitoring stations located in the central and south-western regions of the Silesian voivodeship and in the western part of the Opole voivodeship:

- Wodzisław Śląski, 1 Gałczyńskiego Street (50.0075000°N, 18.4565418°E);
- Zabrze, 34 M. Skłodowskiej-Curie Street (50.3148000°N, 18.7733030°E);
- Kędzierzyn-Koźle, 5 Bolesława Śmiałego Street (50.3493200°N, 18.2359361°E).

The choice of measurement points was a compromise between ensuring the representativeness of receptors and the practicality of connecting research equipment (mobile laboratory) and the availability of complete data at monitoring stations (Wodzisław Śląski, Zabrze, Kędzierzyn-Koźle).

Methods

In diagnostic processes, the so-called synthetic measures derived from multi-criteria decision-making methods (*Multi Attribute Decision Making – MADM*) are becoming popular. These methods allow for the determination of synthetic evaluation indicators (scalars), taking into account the values of many features/variables and factors that interact simultaneously. They also provide flexibility in assigning weights to those factors, allowing for the creation of aggregate values (measures) that can replace the entire set of features/variables and factors describing the object. What sets multi-criteria methods apart is their approach to handling directly incomparable criteria, which may belong to different attribute domains. Within the generalized classification of Multi Attribute Decision Making, there are two subsets of methods:

- the first subset comprises the so-called methods from the French school. The methods of this subset classify the

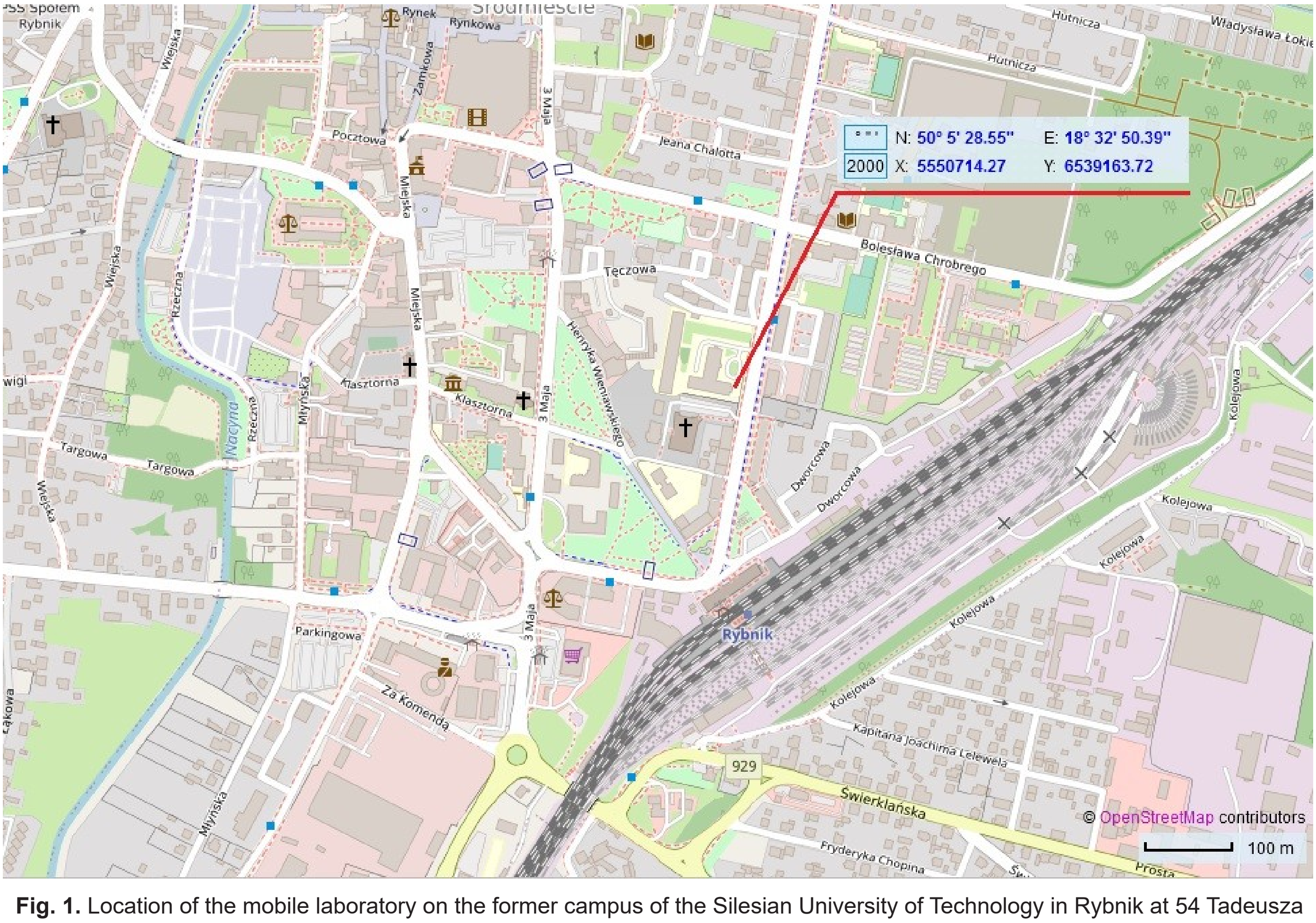

Fig. 1. Location of the mobile laboratory on the former campus of the Silesian University of Technology in Rybnik at 54 Tadeusza Kościuszki Street (Geoportal2.pl 2023).

examined objects by determining appropriate thresholds of mutual dependencies (e.g., in ELECTRE methods, these threshholds are based on conditions of compliance and non-compliance);
- the second subset includes the so-called methods from the American school, such as Z. Hellwig's method, Simple Additive Weighting (SAW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). In these methods, the unification of the domains of the compared criteria allows for direct comparison among them.

Multi-criteria assessment using the TOPSIS method – theoretical foundations

In the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), which is a modification of the Simple Additive Weighting (SAW) method, linear scaling is replaced by non-linear transformations. The TOPSIS method compares objects, also known as variants, with abstract weighted reference solutions represented by the ideal solution vector (pattern) and the negative ideal vector (antipattern). To evaluate the object and facilitate its comparison with others, the Euclidean distance between the vector constituting the image of the examined object and the ideal and negative ideal vectors must be measured. The object with the smallest distance from the ideal vector and the largest distance from the negative ideal vector is considered to be the "best" (Bąk 2016, Behzadian et al. 2012, Boran et al. 2009, Chen 2000, Dymova et al. 2013, Hwang and Yoon 1981, Roszkowska and Kacprzak 2016, Shih et al. 2007, Wang and Chang 2007, Yazdi 2015).

The structure of the TOPSIS synthetic measure includes the following stages (Bąk 2016, Behzadian et al. 2012, Boran et al. 2009, Chen 2000, Dymova et al. 2013, Hwang and Yoon 1981, Roszkowska and Kacprzak 2016, Shih et al. 2007, Wang and Chang 2007, Yazdi 2015):

STEP 1: normalization of variables (quotient transformation):

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{1}$$

where x_{ij} – observation of the j-th variable (descriptive feature) for the object i.

STAGE 2: defining the coordinates of the pattern:

$$z_{0j}^{+} = \begin{cases} max_i\{z_{ij}\} & for\ variables\ being\ stimulants \\ min_i\{z_{ij}\} & for\ variables\ being\ destimulants \end{cases} \tag{2}$$

where:
– stimulant – a descriptive feature/variable characterized by high values that are desirable from the perspective of the diagnosed problem, while low values are considered undesirable;
– destimulant – a descriptive feature/variable characterized by low values that are desirable from the perspective of the diagnosed problem.

STAGE 3: defining the coordinates of the antipattern:

$$z_{0j}^{-} = \begin{cases} min_i\{z_{ij}\} & for\ variables\ being\ stimulants \\ max_i\{z_{ij}\} & for\ variables\ being\ destimulants \end{cases} \tag{3}$$

STAGE 4: determining the distance of objects from the pattern:

$$d_{i0}^{+} = \sqrt{\sum_{j=1}^{m} \left(z_{ij} - z_{0j}^{+}\right)^2} \tag{4}$$

STAGE 5: determining the distance of objects from the antipattern:

$$d_{i0}^{-} = \sqrt{\sum_{j=1}^{m} \left(z_{ij} - z_{0j}^{-}\right)^2} \tag{5}$$

STEP 6: determining the aggregate value :

$$q_i = \frac{d_{i0}^{-}}{d_{i0}^{+} + d_{i0}^{-}} \quad with\colon q_i \in [0;1] \tag{6}$$

Results and Discussion

The measurement locations were interpreted as objects/ components of the set of measurement points P:

$$P = [P_i] \tag{7}$$

where i – number of component / number of measuring station / assessed object.

As part of the presented example:
- $i = 1$ – number of object assigned to the mobile laboratory on the former campus of the Silesian University of Technology in Rybnik;
- $i = 2$ – number of object assigned to the measuring station in Wodzisław Śląski;
- $i = 3$ – number of object assigned to the measuring station in Zabrze;
- $i = 4$ – number of object assigned to the measuring station in Kędzierzyn-Koźle.

For the purposes of multidimensional assessment, each of the above-mentioned objects/points was described in three-dimensional space based on three dimensions/features/ coordinates corresponding to average concentrations of:
dust PM_{10} $[\mu g/m^3]$ ($j = 1$),
carbon monoxide (CO) $[\mu g/m^3]$ ($j = 2$),
nitrogen dioxide (NO_2) $[\mu g/m^3]$ ($j = 3$).
Thus, the measurement results were summarized in the form of a matrix:

$$X = [x_{ij}] \tag{8}$$

where:
i – assessed object;
j – dimension/feature/coordinate of the object.
The exemplary values of average concentrations recorded on selected days in February 2023 are presented in Table. 1.

All the examined features exhibit the characteristics of destimulants, meaning they display a negative correlation with the dependent variable, which in this case is the level of average concentrations of dust and gaseous pollutants present in the atmospheric air. The normalized input data are presented

Tab. 1. Average values of PM10 dust, CO and NO_2 concentrations at selected measurement points (exemplary values recorded in February 2023) - input data.

Matrix of measurement results recorded on February 1, 2023 (average values)			Matrix of measurement results recorded on February 2, 2023 (average values)			Matrix of measurement results recorded on February 3, 2023 (average values)		
13.821	0.215	20.499	10.104	0.132	15.194	14.088	0.166	20.285
17.950	0.321	13.683	13.263	0.254	7.254	19.796	0.258	15.342
12.700	0.242	15.417	9.633	0.200	9.246	16.254	0.258	16.488
6.000	0.321	10.229	4.504	0.308	9.871	8.421	0.329	9.425
Matrix of measurement results recorded on February 4, 2023 (average values)			Matrix of measurement results recorded on February 26, 2023 (average values)			Matrix of measurement results recorded on February 27, 2023 (average values)		
8.948	0.070	8.332	13.094	0.203	11.144	18.879	0.220	16.951
15.104	0.204	5.079	20.992	0.492	7.600	23.671	0.521	15.250
11.663	0.204	4.588	13.742	0.238	7.104	18.658	0.288	15.396
8.425	0.313	3.992	10.383	0.467	8.454	13.696	0.492	12.808

Tab. 2. Average values of PM_{10} dust, CO and NO_2 concentrations at selected measurement points (exemplary values recorded in February 2023) - normalized values (z_{ij}).

Matrix of measurement results recorded on February 1, 2023 – normalized values			Matrix of measurement results recorded on February 2, 2023 - normalized values			Matrix of measurement results recorded on February 3, 2023 – normalized values		
0.519	0.386	0.665	0.511	0.284	0.704	0.463	0.320	0.639
0.673	0.576	0.444	0.671	0.545	0.336	0.651	0.498	0.483
0.476	0.434	0.500	0.487	0.429	0.428	0.534	0.498	0.519
0.225	0.576	0.332	0.228	0.662	0.457	0.277	0.634	0.297
Matrix of measurement results recorded on February 4, 2023 – normalized values			Matrix of measurement results recorded on February 26, 2023 - normalized values			Matrix of measurement results recorded on February 27, 2023 – normalized values		
0.394	0.163	0.725	0.434	0.272	0.639	0.495	0.274	0.559
0.665	0.473	0.442	0.696	0.659	0.436	0.621	0.649	0.503
0.514	0.473	0.399	0.456	0.318	0.408	0.490	0.358	0.507
0.371	0.725	0.347	0.344	0.625	0.485	0.359	0.613	0.422

Tab. 3. Coordinates of patterns (z_{0j}^{+})

Coordinates of patterns for 01/02/2023			Coordinates of patterns for 02/02/2023			Coordinates of patterns for 03/02/2023		
0.225	0.386	0.332	0.228	0.284	0.336	0.277	0.320	0.297
Coordinates of patterns for February 4, 2023			Coordinates of patterns for February 26, 2023			Coordinates of patterns for February 27, 2023		
0.371	0.163	0.347	0.344	0.272	0.408	0.359	0.274	0.422

Tab. 4. Coordinates of antipatterns (z_{0j}^{-})

Coordinates of antipatterns for 01/02/2023			Coordinates of antipatterns for 02/02/2023			Coordinates of antipatterns for 03/02/2023		
0.673	0.576	0.665	0.671	0.662	0.704	0.651	0.634	0.639
Coordinates of antipatterns for February 4, 2023			Coordinates of antipatterns for February 26, 2023			Coordinates of antipatterns for February 27, 2023		
0.665	0.725	0.725	0.696	0.659	0.639	0.621	0.649	0.559

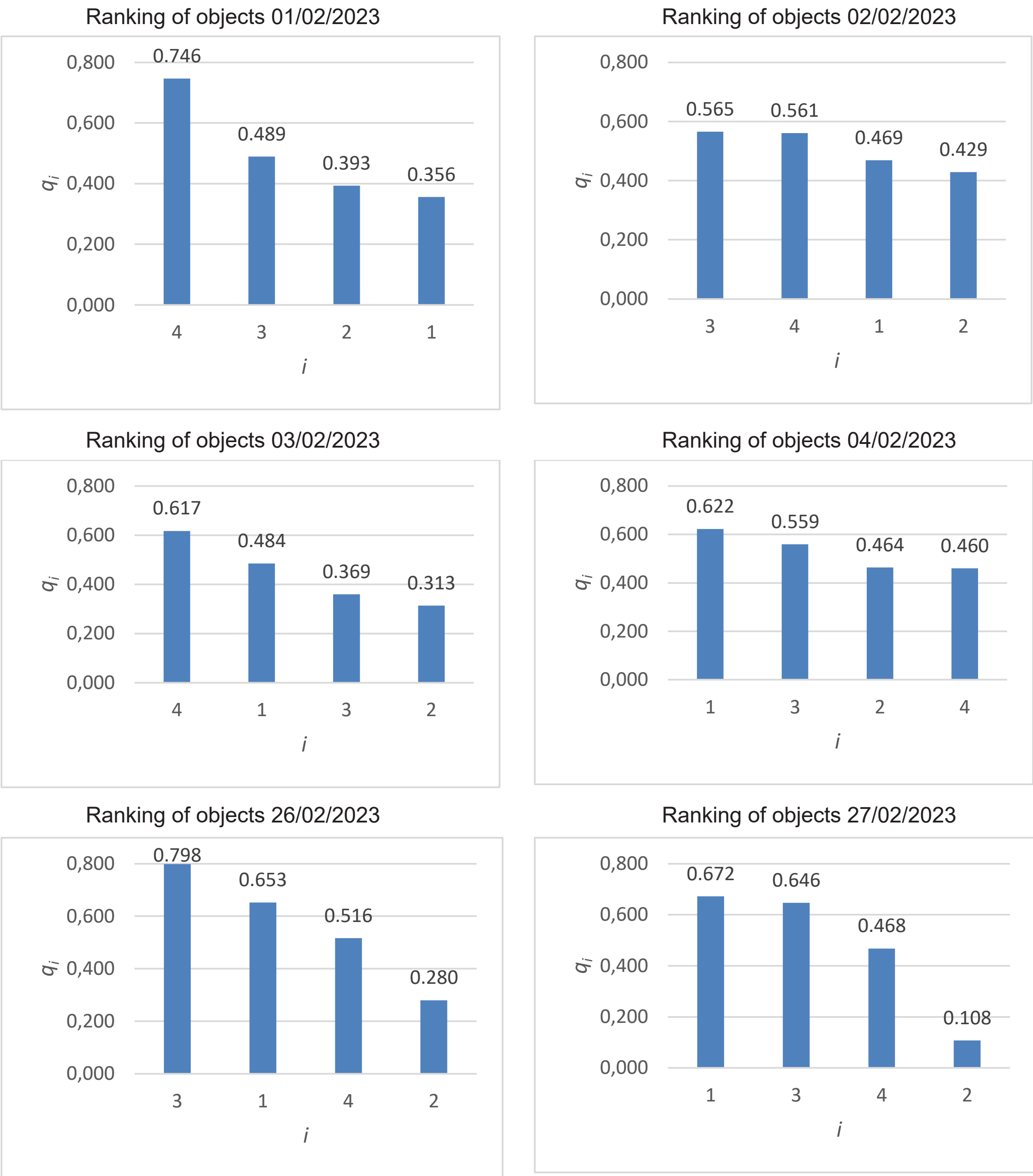

Fig. 2. Rankings of objects

in Table 2, while the compilation of the coordinates of patterns and antipatterns is provided in Tables 3 and 4.

The determined distances of the objects from the patterns (d_{i0}^{+}) and from anti-patterns (d_{i0}^{-}) allowed for the calculation of aggregate values (q_i) (Tab. 5), which in turn enabled the development of the compilation of objects based on rankings (classification in the order of numerical values (from the largest values to the smallest values). In this case i is the number of the object.) (Fig. 2).
Average aggregated values ($\bar{q}_i$) for the month of February 2023 are presented in Tab. 6.

Tab. 5. Aggregate values (q_i)

	q_i					
i/date	01/02/2023	02/02/2023	03/02/2023	04/02/2023	26/02/2023	27/02/2023
1	0.356	0.469	0.484	0.622	0.653	0.672
2	0.393	0.429	0.313	0.464	0.280	0.108
3	0.489	0.565	0.360	0.559	0.798	0.646
4	0.746	0.561	0.617	0.460	0.516	0.468

Tab. 6. Average aggregated values ($\bar{q}_i$) for the month of February 2023.

i	$\bar{q}_i$
1	0.486
2	0.326
3	0.578
4	0.664

Conclusions

For the diagnosed objects (measuring stations monitoring air quality in the cities of Wodzisław Śląski, Zabrze, and Kędzierzyn-Koźle, as well as at the location of the mobile laboratory), the measurement results of the concentration of PM_{10} dust, carbon monoxide, and nitrogen dioxide in the air can be interpreted in two ways :

a) The final results as obtained as part of the single-criterion assessment of the threat to the anthropogenic environment: each i-th object is separately evaluated within the j-th dimension/feature/coordinate of the object/criterion. Through this assessment, it becomes possible to develop partial rankings of objects for each criterion and to generate air quality maps, for instance, based on the Polish Air Quality Index (AQI 2023) recommended by the Chief Inspectorate of Environmental Protection (AQI);

b) Partial results are obtained as part of the multi-criteria assessment of the threat to the anthropogenic environment. In this scenario, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was used, utilizing measurement results to calculate an aggregate (synthetic) final assessment of the threat level.

Following the analysis of the measurement results as part of the single-criterion assessment, it can be concluded that only on February 26, 2023 and February 27, 2023, at the point/object $i = 2$ (the measuring station in Wodzisław Śląski), the air quality was good (the concentrations of PM_{10} dust were respectively: 20.992 $[\mu g/m^3]$ and 23.671 $[\mu g/m^3]$). On the remaining days, according to the AQI, air quality was classified as "very good", indicating that the concentration of PM_{10} dust did not exceed 20.000 $[\mu g/m^3]$, carbon monoxide remained below 2,499.000 $[\mu g/m^3]$ and nitrogen dioxide concentration did not exceed 40.000 $[\mu g/m^3]$ at all monitoring locations.

In the computational example, the lowest concentrations of PM_{10} dust were recorded at the measuring point $i = 4$, located at the measuring station in Kędzierzyn-Koźle. The lowest concentrations of carbon monoxide were recorded at the point $i = 1$, specifically at the location of the mobile laboratory on the former campus of the Silesian University of Technology in Rybnik. Regarding nitrogen dioxide, the lowest concentrations were recorded four times at the measuring station in Kędzierzyn-Koźle, with measurements recorded on February 1, 2023, February 3, 2023, February 4, 2023, and February 27, 2023.

As part of the multi-criteria assessment, considering all factors simultaneously influencing the selected measurement points, namely, the concentration of PM_{10} dust, CO and NO_2, it can be concluded that on the analyzed days, the objects numbered 1, 3 and 4 had the highest aggregate value q_i twice:

- $i = 1$: $q_1 =$ 0.622 (on 04/02/2023) and $q_1 =$ 0.672 (on 27/02/2023);
- $i = 3$: $q_3 =$ 0.565 (on 02/02/2023) and $q_3 =$ 0.798 (on 26/02/2023);
- $i = 4$: $q_4 =$ 0.746 (on 01/02/2023) and $q_4 =$ 0.617 (on 03/02/2023).

Moreover, based on the average values $\bar{q}_i$ per month (February 2023), the most favorable (least harmful) conditions concerning the presence of PM_{10}, CO and NO_2 were recorded at the measurement station located in Kędzierzyn-Koźle ($\bar{q}_4 = 0.664$).

The worst results (regarding the total concentration of PM_{10}, CO, NO_2) were recorded four times at the measurement station in Wodzisław Śląski (i = 2): the aggregate values (q_2) of: 0.429; 0.313, 0.280, and 0.108 are the lowest values determined for February 2, 2023, February 3, 2023, February 26, 2023 and February 27, 2023, respectively.

The most unfavorable conditions related to the presence of PM_{10}, CO and NO_2 during the month of February 2023 were recorded at the measurement station located in Wodzisław Śląski ($\bar{q}_2 = 0.326$).

In the authors' opinion, utilizing the Technique for Order Preference by Similarity to Ideal Solution or another multi-criteria method alongside conducting measurements using a mobile laboratory serves two main objectives:

- the generation of synthetic/collective information, especially crucial in crisis situations where multiple harmful/burdensome substances exceed permissible values, is one goal. In the analyzed computational example, although the air quality indexes indicating good or very good air quality, having access to quantitative information considering all recorded environmental parameters could significantly affect the quality of decisions making. In this case, we are facing a typical multi-criteria task in which it is possible to simultaneously optimize the values of n functions of the objectives/criteria;
- carrying out air pollution measurements at points designated as "sensitive infrastructure", such as schools, kindergartens, and hospitals, often located far from existing monitoring stations, significantly enhances the capability to generate more detailed environmental maps (air quality maps). It is crucial to compare the results of substance concentration measurements with observations of atmospheric conditions like wind direction and speed, temperature, air pressure and humidity, to determine the existing correlations. This comparison is especially important for estimating threats related to air pollution, developing risk maps for regions, or defining preventive action scenarios. For example, using Pearson's linear correlation coefficient (r_{xy}), it was observed in February 2023, at object $i = 1$ (the former campus area of the Silesian University of Technology in Rybnik), that the correlation between the PM_{10} dust concentration and air temperature, as well as wind speed, was moderately negative and amount to: $r_{xy} = -0.469$ and $r_{xy} = -0.598$, respectively.

Similarly, moderate negative correlations were found between carbon monoxide concentration and air temperature, as well as between carbon monoxide concentration and wind speed (Pearson's linear correlation coefficient is -0.446 and -0.598, respectively) and between nitrogen dioxide concentration and air temperature or between nitrogen dioxide concentration and wind speed (Pearson's linear correlation coefficient is: - 0.231 and - 0.681, respectively). However, a moderately positive correlation was observed between nitrogen dioxide concentration and wind direction ($r_{xy} =$ 0.514). Positive, albeit low, correlations were noted between PM_{10} dust concentration and wind direction ($r_{xy} = 0.372$) and between carbon monoxide concentration and wind direction ($r_{xy} = 0.358$). These correlations, although weak, became evident under prevailing winds from the south and southwest. This state of affairs could be attributed to the lack of industrial plants in the vicinity of the measurement point, with pollutants primarily originating from gradually modified heating systems supplying residential infrastructure.

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Data Availability

Data are available from the corresponding author on reasonable request.

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