SIMULATION OF ATMOSPHERIC DISPERSION OF POLLUTANT EMISSIONS FROM A COGENERATION POWER PLANT USING THE GAUSSIAN MODEL

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This study presents an analysis based on the dispersion of atmospheric pollutants resulting from a cogeneration power plant, using the Gaussian model. The objective of the research is to evaluate the impact generated on the environment as a result from energy production. The study integrates the emission source and meteorological parameters, as well as dispersion coefficients, to determine the amount of pollutant concentrations recorded at local level. The simulation shows that the maximum values of concentration for analyzed pollutants (NO_x, SO_2, CO, VOCs) levels are still generally below the ambient air quality standard values set by Law No. 104/2011, suggesting a minimal background pollution contribution.

Keywords: atmospheric pollution, dispersion, Gaussian model, air quality, impact, emissions

1. Introduction

Air is an environmental factor that significantly impacts human health, ecosystem's development and climate. Children, pregnant women, elderly persons over 65 years of age, and persons suffering from respiratory and cardiovascular diseases are more sensitive to the air pollution. The latest scientific knowledge regarding the links between both short- and long-term exposure to air pollution and adverse health effects, remarks that, globally, air pollution is responsible for about 7 million premature deaths per year due to a wide range of diseases, including stroke, chronic obstructive pulmonary disease, trachea, bronchus and lung cancers, aggravated asthma and lower respiratory infections. [1-3] Fine particulate matter (PM 2.5) is the air pollutant driving the most significant health problems and premature mortality due to its diameters less than 2.5 micrometers that can penetrate deeply into the lungs. In 2021, 97 % of the urban population was exposed to concentrations of fine particulate matter above the health-based guideline level set

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by the World Health Organization. [2] Even though every child has the right to breathe clean air to grow up healthy, globally, 93 % of children live in areas where air quality is considered unhealthy. [4] Both terrestrial and aquatic ecosystem protection is also very important for society due to numerous ecosystem services provided for human wellbeing and quality of life. Exposure of ecosystems to key air pollutants leads to negative effects like eutrophication, acidification, biodiversity loss, damage to agricultural crops, forests and plants. [5] Emission of pollutants (including greenhouse gases) into the air can result in changes to the climate with important consequences for society.

In this context, the mathematical dispersion modelling of atmospheric pollutants represents a very useful tool for air quality assessment and air pollution forecasting. The research conducted in the field of mathematical dispersion modelling of pollutants in the atmosphere is important because through modelling we can assess the environmental impact for air pollution sources like power plants, factories, highways before they are built, and forecast the impact of possible accidents. [6] Dispersion models are also used to design air quality monitoring networks, to estimate ambient concentrations and deposition rates of pollutants emitted in the atmosphere from local to regional scale, and to develop strategies for reducing emissions of atmospheric pollutants to respect air quality standards. [6]

Various types of dispersion models were developed (Gaussian plume model, Lagrangian puff models, Trajectory or Eulerian models) to calculate pollutants concentration at local or regional scale, driven by different approaches (simulating passive/chemically active compounds, wet and dry deposition) in different terrain conditions (plain, urban, complex), using input data (source characteristics, meteorological and emissions data). [7]

In the current study a Gaussian model was used to simulate the dispersion of pollutants emitted into the atmosphere by a cogeneration power plant. This plant is in a university campus in Bucharest, the capital of Romania. To evaluate the pollutants' spatial distribution and possible environmental impact, this study aims to simulate the transportation and dispersion of pollutants emitted into the atmosphere from a natural gas-powered cogeneration plant. The model's output data were finally compared to the health-based guideline levels set by Law no. 104/2011 which introduced in the national legislation the provisions of European Directive 2008/50/EC on ambient air quality and cleaner air for Europe. Another objective consists of developing a measures plan to maintain air quality where it respects air quality standards and to improve it in other cases when the limit values set by the regulation in force are exceeded.

2. Methodology

Air dispersion modelling study was conducted using IMMI software which covers different applications, ranging from noise level prediction to air pollution modelling. IMMI is a professional software package. It was developed by the Wölfel Group, a German technology company, being employed in this research for the purpose of environmental and human health impact assessments. The software provides an intuitive graphical interface, integrating dispersion models based on the German regulatory framework TA Luft (Technical Instructions for Air Quality Control), enabling the estimation of pollutant concentrations at ground level. IMMI allows a spatial visualization of pollutant dispersion, facilitating the identification of areas most affected by atmospheric pollution, which supports environmental authorities in assessing air quality compliance.

IMMI includes two versions of the TA Luft guide, namely TA Luft 1986, which incorporates the Gaussian dispersion model, and TA Luft 2021, which applies the Lagrangian particle dispersion model. TA Luft 1986 was used in this study, because it is applicable to stationary point sources of pollution, such as power plants. The Gaussian model was used to calculate ground level concentrations of the main pollutants emitted into the atmosphere by the cogeneration power plant.

The dispersion research was conducted at local scale for an urban built-up area from Bucharest, the capital of Romania. In line with the legal regulations currently in force in Romania, which transpose the provisions of the European Directives into national legislation, four main pollutants were analyzed: nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs).

The spatial dispersion of the pollutants was estimated taking into account essential parameters such as meteorological and emission data, source characteristics and terrain configuration. These input data were converted into a compatible format with the technical specifications of IMMI software.

The influence of the atmosphere is introduced into the dispersion models through meteorological data necessary for reproducing the structure of the atmospheric boundary layer. The main meteorological variables that allow estimating concentration at ground level at a certain distance from the source are the wind direction and speed, as well as the characteristics of turbulence. The concentration of pollutants in the atmospheric boundary layer depends also by the terrain configuration which can influence the pollutants' dispersion into the atmosphere. The higher roughness of terrain, associated with tall buildings in urban areas, affects local wind field and thermal stratification. Cities usually experience so-called "canyon street" and "urban heat island" effects which have important consequences on local air quality.

The output data of the modelling software are represented by the isopleths, where each color represents the concentration range of pollutant gases (Figs. from no. 4 to no. 7). The numerical values of ground level concentrations were compared to the health-based guideline levels set by Law no. 104/2011 regarding ambient air quality. The ground level concentrations of analyzed pollutants were below the values set by regulatory guidelines.

In this study, background pollution was not considered, as the analysis was focused exclusively on assessing the impact of a point source by using the Gaussian dispersion model implemented in IMMI software. Considering that the chosen pollution source is a cogeneration power plant operating on natural gas, which is often considered a cleaner alternative because it is characterized by low pollutant emissions, it was desired to determine the extent to which the resulting concentrations emissions may represent a risk to the environment and human health.

2.1. Description of the study area and the power plant

Bucharest is the capital and largest city of Romania. This is in the south-east of the country, and it has a population of 1.717 million inhabitants, according to the 2021 census. [8] The city area is 240 km^2, resulting in a population density of 7154 inhabitants/km^2.

The cogeneration power plant is in western part of Bucharest, at an university campus. It includes two Jenbacher internal combustion engines of 0.835 MW_e power capacity each, and three Hoval hot water boilers of 6.98 MW_{th} each. This combined heat and power installation operates on natural gas, and it has a total thermal power of 20.94 MW_{th}, and an electric power of 1.67 MW_e. Another significant sources of pollution near the study area include busy roads and a large thermoelectric power plant (100 MW total electric power and 307 Gcal/h total thermal power) operating exclusively on natural gas. These line and point sources contribute to increasing the level of pollution in the area. The physical parameters of the cogeneration power plant used for dispersion study are presented in Table 1.

Table 1

Physical parameters of the cogeneration power plant

Source	Stack diameter [m]	Gas velocity [m/s]	Stack height [m]	Temperature [^{0}C]
Hot water boiler 1	0.8	8.8	23	143
Hot water boiler 2	0.8	7.4	23	143
Hot water boiler 3	0.8	8.6	23	131
Combustion engine MG 1	0.3	30.8	20	478
Combustion engine MG 2	0.3	30.8	20	457

2.2. Dispersion model characteristics

IMMI dispersion model was selected depending on the aim of the research, the availability of input data, the scale at which the dispersion and transport processes were studied, and according to the national legal requirements. The pollutants module in IMMI features the calculation of dispersion of gas, dust and odour according to the gaussian plume model.

The most widely used dispersion model for air pollutants is the gaussian model. It is based on a simple formula (the advection-diffusion equation in simplified form, as shown in Equation 1) that describes the three-dimensional concentration field generated by a point source, being governed by factors such as emission rate of the pollutant, meteorological conditions, and distance from the source of emission.

$$C\ (x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \cdot exp\left(-\frac{y^2}{2\sigma_y^2}\right) \cdot \left[exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right] \quad (1)$$

Here C is the pollutant concentration [$\mu g/m^3$], Q – emission source rate [g/s], u – wind speed at stack height [m/s], H – effective stack height [m], σ_y and σ_z - dispersion coefficients in the y and z axis [m], y and z – lateral and vertical distance from the plume centerline [m]. The terms σ_y (standard deviation of lateral concentration distribution) and σ_z (standard deviation of vertical concentration distribution) are based on atmospheric stability coefficients, where larger values (usually at greater distances from the source) represent a plume with widespread and low peak, and vice versa. [9]

3. Results and discussions

To determine the level of pollutant concentrations resulting from energy production, IMMI software was applied. IMMI is based on the use of mathematical models (as the Gaussian dispersion model), incorporating essential parameters such as meteorological data, emission source characteristics and terrain configuration.

The first step in performing the simulation was to convert the meteorological data into a compatible format with the technical specifications of the program. To achieve this objective, it was necessary to determine the stability class. The stability class considers meteorological parameters, in particular wind speed, solar radiation, cloud cover and time of day, as described in the Pasquill-Gifford method. There are seven stability classes, numbered from A to G, where A represents the most unstable atmospheric conditions and G is the extremely stable conditions.

The next step was to determine the wind frequency matrix. As shown in Figure 1, the wind frequency matrix was dependent on the wind direction and the stability class. The stability class was defined on the rows and the wind direction on the columns. The values obtained indicate how often a certain wind direction was observed in a certain stability class, respectively the number of occurrences.

Count of stability_class	Column Labels																																		
Row Labels	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**	**230**	**240**	**250**	**260**	**270**	**280**	**290**	**300**	**310**	**330**	**340**	**360**	**Grand Total**
⊟Class D	**2**	**3**	**8**	**19**	**24**	**41**	**33**	**23**	**10**	**7**	**4**	**2**	**2**		**4**	**2**	**2**	**2**	**5**	**6**	**10**	**30**	**31**	**17**	**7**	**4**	**1**	**1**	**3**	**2**	**1**	**3**	**4**	**1**	**314**
1																	1			1															2
1.5									1										2			1													4
2		1		3	4	1	1	3	1	3	1		1		1	1				1		3	2		1								1		29
3	2	2	5	8	5	11	8	12	5	1	2	1			1	1	1	1	1	4	4	4	9	3		2	1		3	2	1	3	3	1	107
4.5			2	7	5	17	12	5	1	2	1	1	1		2			1			4	14	7	7		1		1							91
6			1	1	7	3	6	3	2										1		1	6	11	5	2										49
7.5					1	3	4			1									1		1	2	1	1	2	1									18
9					1	1	1																1	1	1										6
12					1	5	1																		1										8
⊟Class E					**4**	**1**						**1**							**1**	**1**		**3**	**1**	**1**	**1**										**14**
1.5												1																							1
3																				1															1
4.5					3														1			1	1		1										7
6																						2		1											3
7.5						1																													1
9					1																														1
⊟Class F			**1**		**9**	**3**	**4**	**2**						**2**				**1**		**3**		**3**	**6**	**2**		**1**			**1**						**38**
2														1																					1
3			1			1	1	1						1				1		3		1	1	1											12
4.5					3	1	2																2												8
6					5		1															2	1	1					1						11
7.5						1		1																											2
9					1																		2			1									4
Grand Total	**2**	**3**	**9**	**19**	**37**	**45**	**37**	**25**	**10**	**7**	**4**	**3**	**2**	**2**	**4**	**2**	**2**	**3**	**6**	**10**	**10**	**36**	**38**	**20**	**8**	**5**	**1**	**1**	**4**	**2**	**1**	**3**	**4**	**1**	**366**

Fig. 1. Determining the wind frequency matrix

Based on the results obtained, class D has the most occurrences indicating a more predominant wind in these neutral conditions. After obtaining the wind frequency matrix, the meteorological data is converted into the DWD format, known as the German Weather Service (Deutscher Wetterdienst), as showed in Figure 2.

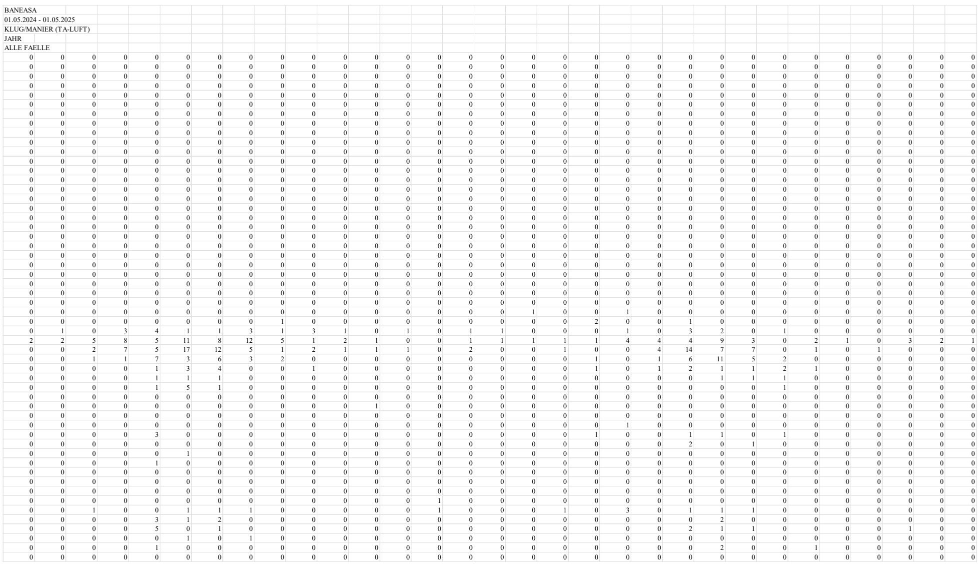

Fig. 2. Conversion of meteorological data into the software required format (Deutscher Wetterdienst format)

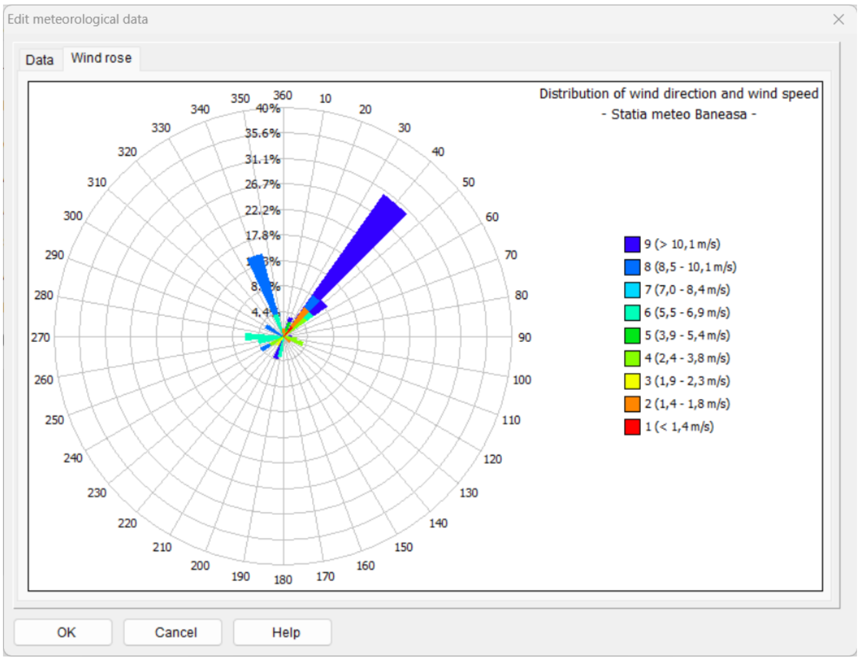

Fig. 3. Wind rose, Source: IMMI software

The first five lines represent the name of the weather station, the period chosen for the simulation and the calculation method used. Meaningful results were observed in cases where the atmospheric stability was classified as neutral (D), stable (E) and very stable (F), the rest of the fields being marked with zero.

After the meteorological data was inserted, the wind rose could be determined. As illustrated in Fig. 3, the wind is predominantly from the NE direction (around 40 degrees). The wind rose indicates the frequency and intensity of wind in different directions. Knowing which way the wind is blowing, we can figure out which path air pollutants will take. This information is essential for assessing the areas most impacted by the dispersion of these contaminants.

Once the wind rose had been established, the dispersion simulation was performed. The results can be visualized in the form of concentration maps providing a better interpretation of the spatial distribution of these pollutants. Following illustrations (from Fig. 4 to Fig. 7) show pollutant dispersion under neutral atmospheric conditions (class D). Stability class D suggests moderate atmospheric turbulence, therefore the highest pollutant concentrations are found near the emission source. The areas marked in red and magenta colors represent the areas where the highest pollutant concentrations were recorded, while the areas in green and yellow indicate the lowest levels of concentrations.

The developed simulation allowed a two-dimensional representation of the pollutant concentration. The highest concentration level was associated with the pollutant carbon monoxide (CO), as illustrated in Fig. 6, and the lowest was found in the case of volatile organic compounds - VOCs (Fig. 7). Low levels of sulfur dioxide concentrations can also be observed in the simulation (Fig. 5). This may result from the dilution of this compound in the atmosphere (as chemical transformation into secondary compounds or wet and dry deposition) or by using advanced emission control technologies (as desulfurization systems).

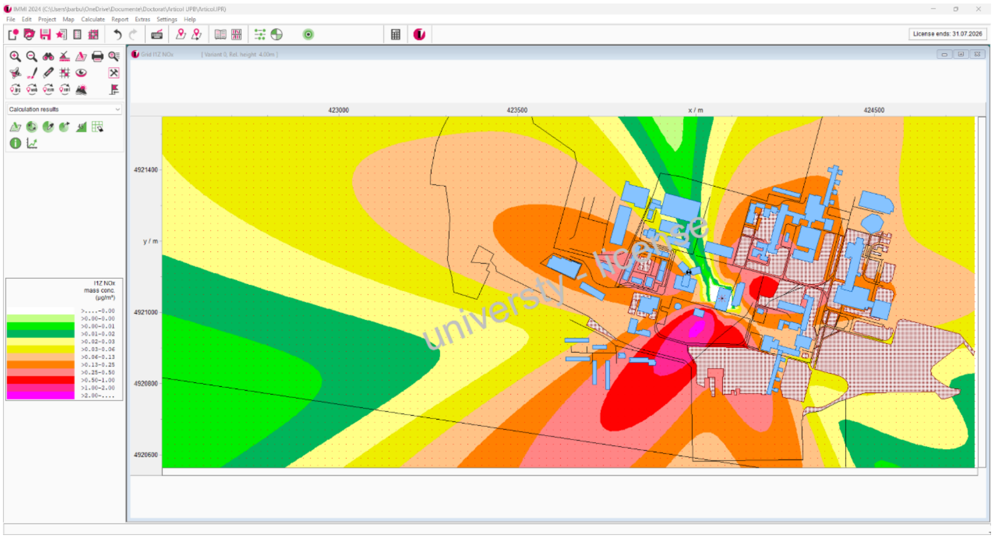

Fig. 4. Simulated distribution of atmospheric NO_x concentrations, Source: IMMI software

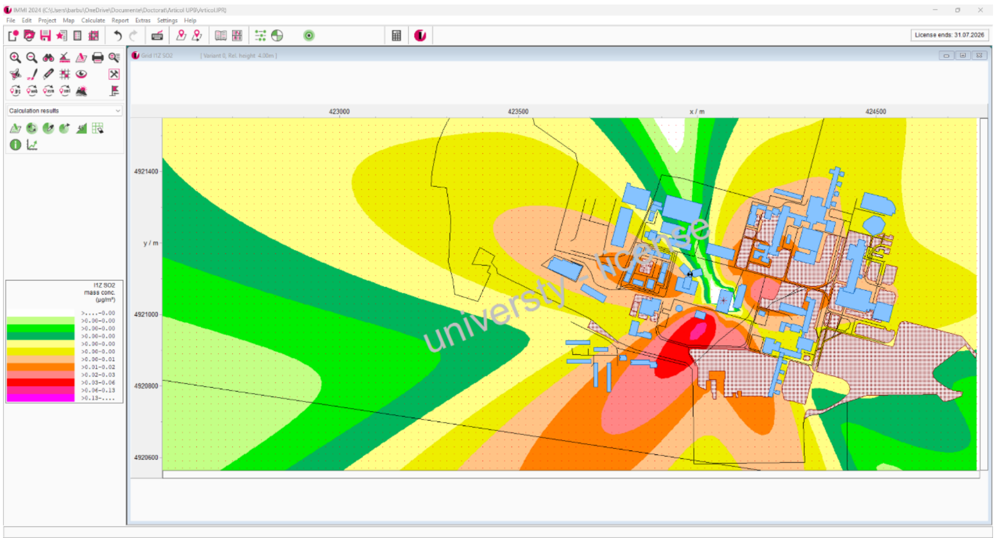

Fig. 5. Simulated distribution of atmospheric SO_2 concentrations, Source: IMMI software

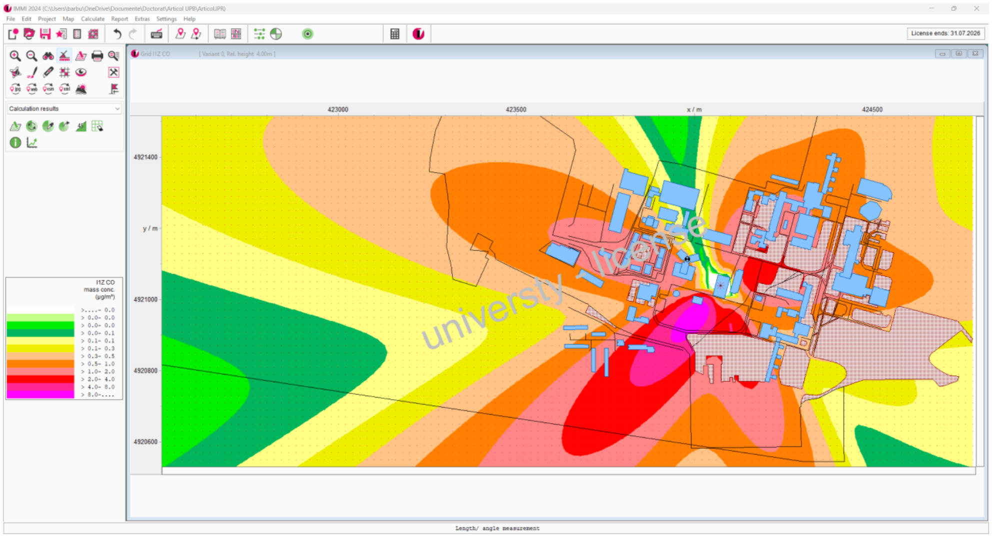

Fig. 6. Simulated distribution of atmospheric CO concentrations,

Source: IMMI software

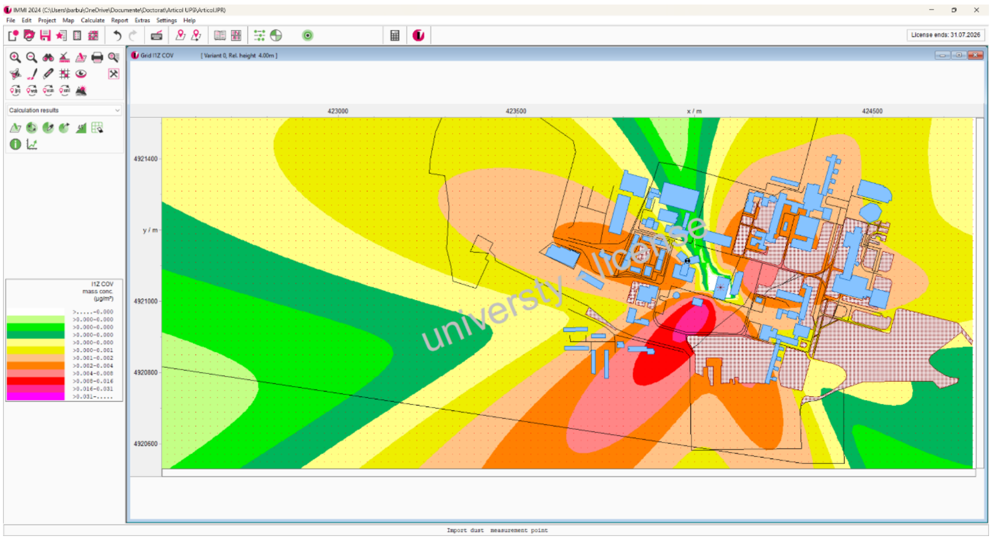

Fig. 7. Simulated distribution of atmospheric VOCs concentrations
Source: IMMI software

As previously mentioned, operating on natural gas, the emission source has a minimal impact on the environment and human health. This is validated by the results obtained from the simulation (NO_x = 2 μg/m^3, SO_2 = 0.13 μg/m^3, CO = 8 μg/m^3 and VOCs = 0.031 μg/m^3), which fall within the limits established by Law no. 104/2011. In the case of NO_x compound, its highest concentration value of 2 μg/m³ was well below the annual thresholds of 30 μg/m³ (for vegetation protection) and 40 μg/m³ (for human health protection). The highest concentration value for SO_2 was considerably lower than both limit values (125 μg/m³ for daily exposure, with only 3 exceedances allowed per year and 350 μg/m³ for hourly exposure, with a maximum of 24 exceedances per year). The sulphur dioxide is regulated by short-term immission values, mainly causing acute health effects rather than chronic ones, and for this reason there are hourly or daily limit values instead of annual limit value.

Similarly, in the case of carbon monoxide (CO), its highest concentration value is far below the annual limit value of 10,000 μg/m³. However, Law no. 104/2011 does not establish a specific limit value for volatile organic compounds (VOCs), but as benzene belongs to this group and its annual limit value in this legislation is 5 μg/m³, no limit value exceedance was observed.

Meteorological parameters, in line with emission source parameters, have had a significant influence on the transport and distribution of pollutants in the atmosphere. For example, higher wind speeds lead to the dispersion of pollutants over longer distances, reducing concentrations near the emission source. Otherwise, lower wind speeds are associated with less dispersion and higher ground-level concentrations. Wind direction is another factor that determines the trajectory of the pollutant plume, being correlated with the area which indicates the highest concentrations of pollutants. The temperature and solar radiation also affect the atmospheric dispersion of pollutants by influencing thermal buoyancy and atmospheric mixing. Regarding the emission source parameters, the height of the stack and its diameter along with the emission rate and the exit velocity of the flue gases are the key factors that determine the concentration of pollutants. [10-12]

These represent only a subset of the factors that influence air quality. Other elements that have important consequences on air quality include land use, chemical transformations that occur in the atmosphere (as oxidation reactions, photochemical reactions or secondary aerosol formation) and background pollution.

4. Conclusions

Air quality is a very important factor for human health, especially for the sensitive population represented by children, pregnant women, elderly persons over 65 years of age, and persons suffering from respiratory and cardiovascular diseases. Also, the air quality affects ecosystem development and climate, having important consequences for society. In this context, the aim of the present research was to assess the pollution impact generated by a natural gas-powered cogeneration plant on air quality through dispersion modelling techniques. Air dispersion modelling study was conducted using IMMI software – a Gaussian dispersion model – which was used to calculate the concentration at ground level for the following pollutants: nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), and volatile organic compounds (VOCs).

The decision to use the Gaussian model to simulate the pollutants dispersion in the atmosphere was based on the computational effectiveness of this mathematical model in assessing the impact generated on the environment and human health.

Based on the meteorological data, the wind rose generated by the IMMI model indicates wind direction which is predominantly from the NE direction. Wind direction is a key factor because it determines the pollutant plume trajectory. Therefore, the plume disperses downwind from source, following the dominant wind direction. For instance, a NE wind will carry the plume toward the SW. The stability class D has the most occurrences indicating a more predominant wind in these neutral conditions.

The model output data, expressed as the highest concentration values for the analyzed pollutants (NO_x = 2 $\mu g/m^3$, SO_2 = 0.13 $\mu g/m^3$, CO = 8 $\mu g/m^3$ and VOCs = 0.031 $\mu g/m^3$), were compared with the health-based guideline levels set by the Law No. 104/2011 regarding ambient air quality. The ground level concentrations of analyzed pollutants were below the values set by regulatory guidelines.

Air quality monitoring supports the minimization of negative effects on the environment and human health. Poor air quality can lead to biodiversity degradation and to diseases development among the population. Therefore, it is aimed that emissions from various sources do not exceed the maximum admissible values established by current legislation.

In general, the location of air pollution sources in urban areas associated with tall buildings can influence the dispersion of pollutants in the atmosphere, leading to their local accumulation. The point source analyzed in this dispersion study complies with air quality legislation, since the combustion process uses natural gas as fuel. Another reason is that the power plant has emission reduction equipment, and it was designed with optimal physical parameters (such as the height and diameter of the stack) for the optimal dispersion of pollutants in the atmosphere.

This study contributes to a better understanding of the modelling techniques for atmospheric pollutant dispersion, serving as a scientific tool for students, teachers and researchers that activate in environmental protection field. Also, atmospheric dispersion modelling represents a modern and powerful tool for environmental authorities to develop air quality management plans, to design air monitoring networks, and to ensure prompt intervention in case of pollution accidents.

Acknowledgments

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