

Applications of Operations Research in Minimizing Emission related Externalities of Power Plants

Pratik Doshi*, Nuti Thakkar**, Pranav Kapoor`, Pranav Thawani``, Prakhhar Pandey````

- * (Student at NMIMS University, VL Mehta Road, Vile Parle, Mumbai
Email: pratikdoshi99@gmail.com)
- ** (Student at NMIMS University, VL Mehta Road, Vile Parle, Mumbai
Email: nutithakkar1259@gmail.com)
- ` (Student at NMIMS University, VL Mehta Road, Vile Parle, Mumbai
Email: pranav413k@gmail.com)
- `` (Student at NMIMS University, VL Mehta Road, Vile Parle, Mumbai
Email: pranavthawani@gmail.com)
- ```` (Student at NMIMS University, VL Mehta Road, Vile Parle, Mumbai
Email: prakharpandey8@gmail.com)

Abstract:

Power generation is a leading contributor to air quality deterioration. This has led to the emergence of basic air quality benchmarks that are supposed to be upheld by power companies. While these decisions are taken keeping the health of the broad environment in mind, little is done to reduce or compensate for the damage caused in the regions surrounding power plants. This research employs pollution measurement models and combines them with Operations Research techniques to come up with solutions that make lives easier for people living around power plants.

Keywords —Plume Dispersion, Optimizing Power Plant Locations, Minimizing Pollution Concentration, Improving Health Standards, Simulation Techniques..

I. INTRODUCTION

“Recent years have witnessed growing concerns about the harmful ramifications of industrial development and urbanization in the form of climate change and global warming (Rohit Nishant, 2012). The findings of the International Panel on Climate Change (IPCC), a body formed by the United Nations (UN), suggest that greenhouse gases (GHGs) are responsible for global warming(National Geographic, 2019). A major source of the GHGs emissions is caused by industrial operations.

The increasing cognizance of adverse environmental impact has resulted in organizational efforts targeted at reducing harmful environmental impact. A recent industry report indicates that IT infrastructure such as data centres contributes to 2% of the annual GHGs emissions (Computerworld, 2007) . This has resulted in the emergence of green IT as a significant component of a broad stream of initiatives focused on improving environmental performance of organizations.

The last three decades have seen a stream of research on the impact of environmental performance and regulations on an organization’s financial

performance. There have been two distinct views on the possible direction of the relationship between environmental performance and organizational performance. The underlying argument is that the drive towards better environmental performance would be achieved by organizational research and operations towards cutting down on emissions. One of the important components of the environmental performance of organizations is GHG emissions, which refers to discharge of gases such as carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and fluorinated gases. These gases trap heat in the atmosphere and thus contribute to global warming and climate change. The GHG emissions are measured and tracked using a protocol developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) (The Greenhouse Gas Protocol Initiative 2011).

The emergence of environmental problems on global forums have led to the development of the concept of Emissions Trading. Given the externalities associated with emissions, every company is allocated limited emission rights. These rights cap the emissions by the operations of individual companies. Companies who have unused rights can sell them to those who have exhausted their rights. This provides a financial incentive for companies to minimize their emissions.”¹ Various studies like (Tim Laing, 2013) and (Xiting Gong, 2013) have been conducted to assess the financial, business and environmental implications of emissions trading and carbon tax.

¹ Content in quotes referred from (Rohit Nishant, 2012)

² Content Referred from (The Guardian, n.d.), (Glick, n.d.), (NASA Earth Observatory, n.d.) and (Wikipedia, n.d.)

II. OPERATIONS RESEARCH

Operations Research Techniques have played a major role in optimizing operations. This area of study has helped in developing strategies that save time, money and energy. It has applications in industries such as airlines, manufacturing, services, military and government. Some business applications of operations research include market strategy planning, capital budgeting with the help of Linear Programming (LP), manpower assignment, machine assignment and space allocation with the help of Assignment and Transportation Models. (Javadi, 2011) published his findings on how principles of operations research were being applied in schools and academic institutions. (Rodolfo C. Salazar, 1968) used simulations and stochastic linear programming to compute expected returns from portfolios of projects.

Operations Research Techniques such as simulation models have been particularly useful in reducing emissions and making key decisions whose ultimate result is reduced environmental damage. Works such as (Najam Khan, 2019) have dived deep into software based simulation that is aimed at minimizing coal transportation cost and electricity transmission loss while keeping emissions under regulatory standards. Other work in the areas of energy and environment that have taken a quantitative approach include (Dang Gu Chai, 2017).

III. OVERVIEW²

Through the course of time, pollution has imperceptibly become one of the most hazardous threats to the environment. As a result of negligence towards strict regulations there has been a

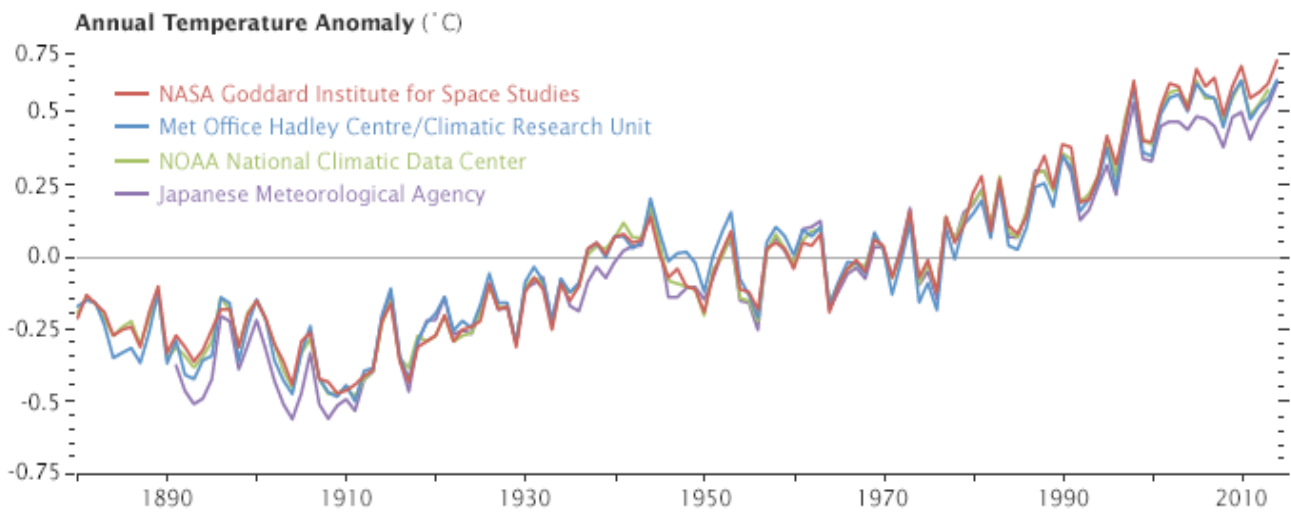
detrimental impact on the environment. Around 700,000 premature deaths are caused due to toxic emissions. To minimize the increasing impact there have been multiple interventions in recent years by many organizations/governments. In the timeline of these interventions there are certain junctures which have been important for the safeguarding of the environmental condition. Some examples of these are the Paris Convention, the United Nations Framework Convention on Climate Change, the Biological Diversity Convention and some local movements such as the Chipko movement. These movements have resulted in strict regulations and colossal punishments for disregarding them. Various studies have been conducted to study the implications of countries individual emissions on a global level. (Welsh, 1990) published the implications of cross border air pollution in Western Europe while keeping the cost element in min. There has been an average implementation of 100 new laws every year since 2009. Some of these rules include legal limits on emission of greenhouse gasses and pollutants and prohibition of use of environmentally toxic materials (Eg: recent ban on one time use plastic). In view of the future trajectory of each country's emission there have also been POAs (plans of action) allocated to each country; These movements have formed POAs to keep annual global warming well under 2 °C. This has been done to provide a guideline for countries to try and maintain coherence between the actual emissions and the predicted emissions. Although there have been multiple treaties, conventions and other plans the global temperature has been constantly rising by approximately 0.2 degrees Celsius every decade. Emission of particulate matter 2.5 (emissions of compounds which are a concern for human health) has increased over time in various countries. As a

result of the global warming, glaciers decrease in a volume of 1.07×10^6 km² every year;

The Kilimanjaro has melted over 80% (Glick, n.d.) and parts of the Himalayas could disappear by 2035. The warming and melting has also heightened the sea by around 19cm and harmed a lot of animal life. Non-compliant countries are having a huge impact on the environment and global warming records have been periodic and constant; Though the punishments are strict it will be a hard task to prevent global warming to increase global temperatures from 1.5°C to 2°C.

With increase in Global Warming caused due to emissions leading to stronger and frequent storms, draughts and increased sea level, it became imperative to find a solution leading to the invent of Renewable Energy. The wide increase in renewable energy - Solar Power, Wind Power, Hydro Power, Ocean Energy, Geothermal Energy, Solar Thermal Heating and Cooling and Biofuels; it has reduced greenhouse gas as well as dust emission. It decreases emission by 81%.

Not only that but models like Energy and R&D Roadmaps and System like Prospective outlook on Long Term Energy have helped minimise emission and stimulate and analyse the economic perspective of world's energy sector.



Source: (NASA Earth Observatory, n.d.)

The figure above sheds light on the historical temperature anomalies as calculated by different research bodies. This can largely be attributed to increasing emission levels across the globe. The primary composition of these emissions is CO₂, SO₂, NO_x, Particulate Matter and varying amounts of toxic metals lead and mercury. Extensive research on the environmental and economic damage caused by emissions has been conducted earlier and their conclusions are exhibited in (Kenneth Gillingham, 2018).

IV. RESEARCH OBJECTIVES

The objective of this paper is to study existing literature on Pollutant Dispersion and Pollutant Exposure Minimizing Techniques and recommend models that can optimize pollutant exposure using constraints not used earlier (Example: Population density of surrounding region). The ultimate goal of the study is to make these models flexible to facilitate easy integration of different pollutant concentration models.

V. METHODOLOGY

Work done by (Najam Khan, 2019) adopted a unique approach of using computer simulations to solve the complex problem of optimising cost while meeting environmental emission standards for power plants. The approach adopted in their research serves as inspiration for this research paper. The model proposed in this paper suggests that an existing Plume Dispersion Model be used to calculate a statistic that can represent the emission related externality associated with setting up a power plant at all possible locations on a 2-D plane surface and optimizing the location of the power plant to minimize the associated externalities. The model also proposes that the population of the habitation areas be taken into account to correctly estimate the associated externality.

VI. LITERATURE REVIEW

This study employees the Gaussian Plume dispersion Model to calculate the concentration of pollutants at

a particular location from the power plant. Numerous other equations have been developed that help in similar calculations under various conditions. “Models like the METI LIS (A. Kouchi, 2004) and AIST-ADMER were developed in Japan to study industrial emissions. The National Institute of Advanced Industrial Science and technology developed the AIST-ADMER model that takes into account metrological data and emission specific characteristics to estimate the chemical concentration of emissions in a particular area. The METI LIS model was developed by the Japanese Ministry of Economy, Trade and Industry to study emissions under various environmental conditions. It was used to calculate emissions using in Vietnam (Nguyen Huu Huan, 2012). (Razi, 2012) used the AIST-ADMER model to estimate regional concentration and distribution of mercury in the Honshu Island. Individual models to study individual gases were also developed.”³ (Hicham Gourgue, 2015) developed models to study nitrous oxide compounds emitted from boilers.

Apart from the models that try to estimate plume dispersion, several scholars have worked on equations that explain plume rise (Seema Awasthia, 2006). In this study, the effective height of the stack was taking into account. The effective height of the stack is a sum of the actual height of the chimney and the natural rise in the emitted gases when they are released. (F.W. Thomas, 1969) came up with the results of a study involving major electricity generation stations in England in 1963. Simulation has been used in earlier research to optimize costs (Zhijie Zhu, 2019).

This area of study is a unique blend of science and operations research where the models are based on the principals of science while their optimization is

achieved from principles of Operations research. Therefore the literature surrounding this field also seeks inspiration from both Scientists and Operations Researchers.

VII. LOCATION OPTIMIZING MODEL

As Stated earlier, the model proposed in this paper employs simulations. The volume of calculations arising out of computing the concentration of pollutants suggests that they be done through software. For the purpose of this paper, a suitable computer algorithm was developed whose results have been displayed. (Figures 1-4)

Key Computations undertaken by the Algorithm:

1. Concentration of Pollutants: The concentration of pollution for every region is calculated using the Gaussian Plume Dispersion Model (Arya, 1999).

$$C = \frac{Q}{\pi \cdot u \cdot \sigma_y \cdot \sigma_z} \cdot e^{\left(\frac{-H^2}{2(\sigma_z)^2}\right)} \cdot e^{\left(\frac{-y^2}{2(\sigma_y)^2}\right)}$$

Where ‘C’ is the concentration in ug/m³, ‘Q’ is the rate of emission of pollutants from the plant in ug/sec, ‘u’ is the velocity of the wind in m/sec at the height where the pollutants are released in the air, sigma y is the horizontal dispersion of plume particles from the central line (absolute trajectory of plume), sigma z is vertical dispersion of plume particles from the central line, ‘H’ is the effective height of the stack (chimney) that is emitting the pollutants and ‘y’ is the Y coordinate of the region. The model calculates the pollution concentration at ground level for a location

³ Referenced from (Najam Khan, 2019)

with X and Y coordinates on a plane. The coordinates of the location are expressed by aligning the x-axis with the trajectory of the prevalent wind.

It should be noted that:

- For every region, only the maximum concentration of pollutants (worst air quality) at ground level is taken into account. The concentration of pollutants is maximum when the region falls on the trajectory of the wind that is carrying the plume. Thus the variable ‘y’ is set to 0 during the calculations
- The pollutant concentration is calculated at ground level. As a result, the variable ‘z’ which appears in the standard version of the equation is ignored above. ‘z’ represents the height of the point from the ground level (which in this case is 0)

2. Weighted Average Exposure (WAE): A weighted average (Investopedia, 2019) of the concentration of pollutants across surrounding areas of habitation, using the population of those areas as weights is used to represent the environmental externality associated with setting up a factory at a particular location.

$$WAE = \frac{\sum c_i . P_i}{\sum P_i}$$

Where ‘C’ is the maximum possible concentration of pollutants in region

‘i’ and ‘P’ is the population of that region.

3. Simulations: The Weighted Average Exposure (WAE) is calculated with reference to every point on the 2D plane where setting up a power plant is possible. The final step is to select the location of the power plant that has the minimum WAE.

Application of the Model: Illustration Region

The Simulation procedure is applied to a 10 km x 10 km plot of land which has 20 inhabited regions with varying population densities in each region. The area under consideration is at sea level, dry and largely devoid of any vegetation. This means there is no need for any deforestation and the only externality associated with setting up a power plant in this region is the resultant pollutant emissions. The 20 inhabited regions are randomly dispersed in the area. The environmental conditions are stable and there is little experience of winds at ground level. This is why the region does not experience dust storms in spite of low green cover in the area.

The region is described keeping in mind the prerequisites of using the Gaussian Plume Dispersion Model. As regions vary, the model may become less accurate. It is therefore recommended to modify the models when dealing with diverse environmental and climatic conditions.

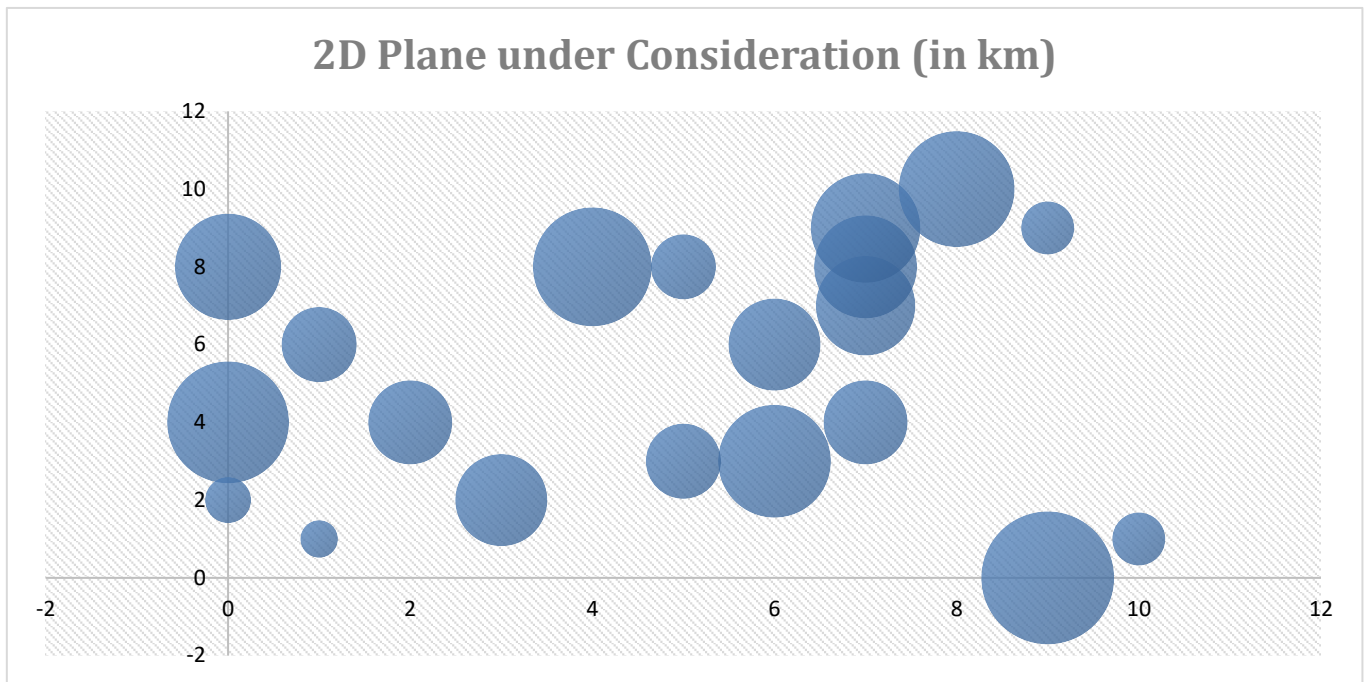


Figure 1: 2-D Plane representation

The region can be visualized with the help of the above map. The map highlights the randomly dispersed habitations (blue bubbles). The size of the bubble highlights the relative population density of that habitation as compared to the others. The area under consideration is only 10 km x 10 km.

Power Plant

The power plant is proposed to have a stack (chimney) height of approximately 100m and the maximum height the plume is expected to rise to is 150m. The average wind speed at the effective height of 150m is assumed to be 10m/sec. The boiler exhaust system will consist of only one blower that can effectively blow out plume at the rate of 500 g/sec.

Pollution Concentration and the Weighted Average Exposure

The weighted average exposure to pollutants is calculated for every possible point where the plant can be set up. The following figure shows the exposure to pollutants by all the inhabited regions when the plant is placed at the coordinates (2,2).

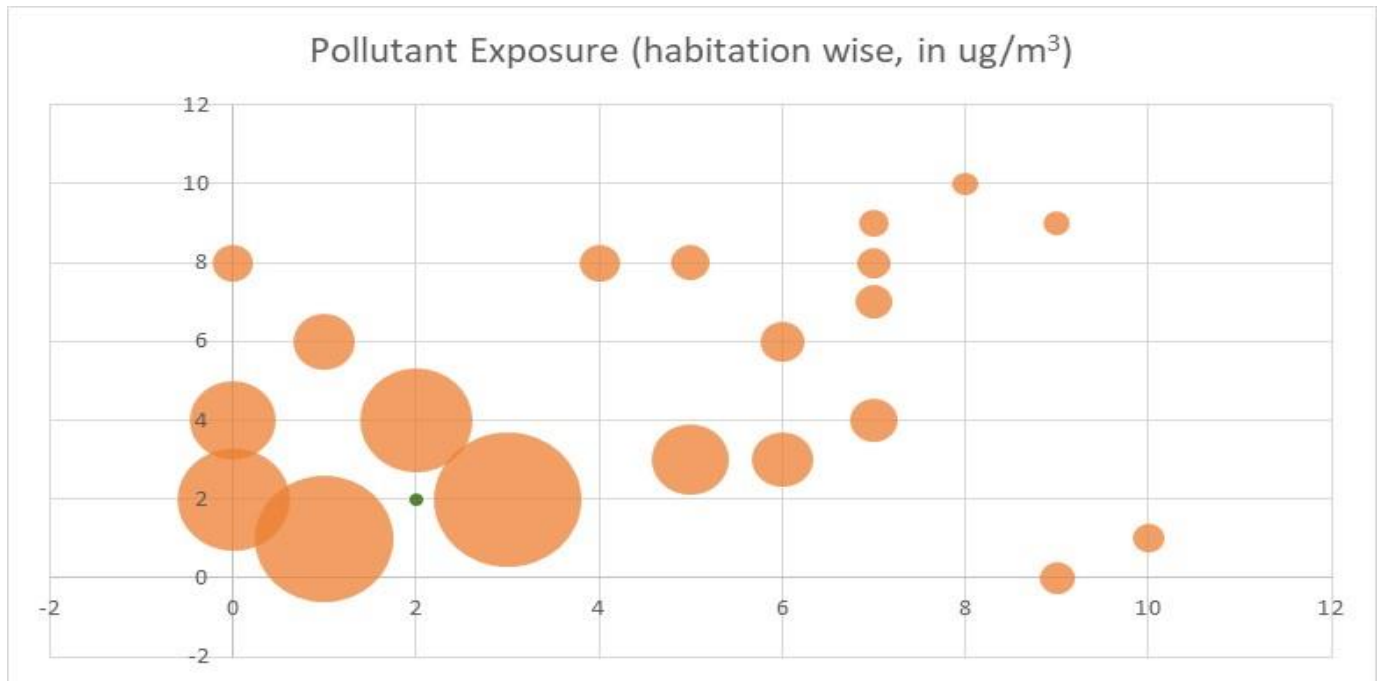


Figure 2: Exposure due to power plant at (2,2)

The power plant is marked by the small green circle. The bubbles represent the habitations and their relative size highlights the exposure to pollutants. In order to arrive at the Weighted Average Exposure (WAE), the average of the pollution concentration of the habited areas is taken, using their respective populations as weights. The WEA for the plant location (2,2) turns out to be 9.48 ug/m^3 . The WEA for all the possible plant locations are calculated to estimate the location-wise impact of the power plant. It should be noted that there may be water bodies, highways, habitations and government reserved forests in the area under consideration. The location of such structures must be excluded from the simulation process as setting up a power plant is not possible in those areas. The simulation process itself operates on a degree of precision. It is possible to achieve a degree of precision to the last metre.

The figure below summarizes the results of the simulation algorithm developed.

		X										
		0	1	2	3	4	5	6	7	8	9	10
Y	0	4.087	4.683	5.223	5.557	5.646	5.731	6.074	7.129	8.935	-	8.349
	1	5.532	-	7.445	7.882	8.140	8.061	8.205	8.432	9.507	9.531	-
	2	-	8.571	9.482	-	10.625	11.308	11.319	10.509	9.049	8.120	6.662
	3	9.828	11.203	11.222	11.438	12.058	-	-	12.220	9.693	7.315	5.727
	4	-	12.149	-	11.352	11.843	13.460	14.342	-	10.048	7.339	5.467
	5	10.913	12.164	11.489	11.021	11.359	13.086	14.334	13.474	10.629	7.612	5.576
	6	9.786	-	10.676	10.866	12.044	13.879	-	14.859	11.975	8.345	5.926
	7	9.452	10.272	10.335	11.667	13.536	15.901	17.487	-	13.968	9.568	6.476
	8	-	9.205	9.543	11.330	-	-	18.108	-	15.911	10.824	7.131
	9	7.065	7.618	7.849	9.729	11.665	13.677	15.918	-	15.845	-	7.386
	10	4.988	5.403	5.895	6.941	8.310	9.759	12.114	13.923	-	10.371	6.908

Figure 3: Results of the simulation algorithm

The precision on the algorithm was set to 1km to facilitate presentation of the results on a table. The WAE values in each cell are expressed in $\mu\text{g}/\text{m}^3$. The least WAE occurs in cell (0,0). This implies that setting up the power plant at that location will result in least externality. The empty cells represent the inhabited areas. They are left empty because it is not possible to place a power plant there. The optimum value is $4.087 \mu\text{g}/\text{m}^3$. The table also makes it easy to analyse the externalities and allow the decision maker to select the second or third best location if the first is unavailable. Figure 4 depicts the scenario when the power plant is placed at (0,0), which is the optimal point. The size of the bubbles represent the degree of concentration of pollutants. The larger the bubbles, the greater is the exposure. It should be noted that there is a striking difference

in the size of bubbles in Figure 2 and that in Figure 4. On an average, the bubbles are smaller in Figure 4, implying lower exposure levels on average in Figure 4.

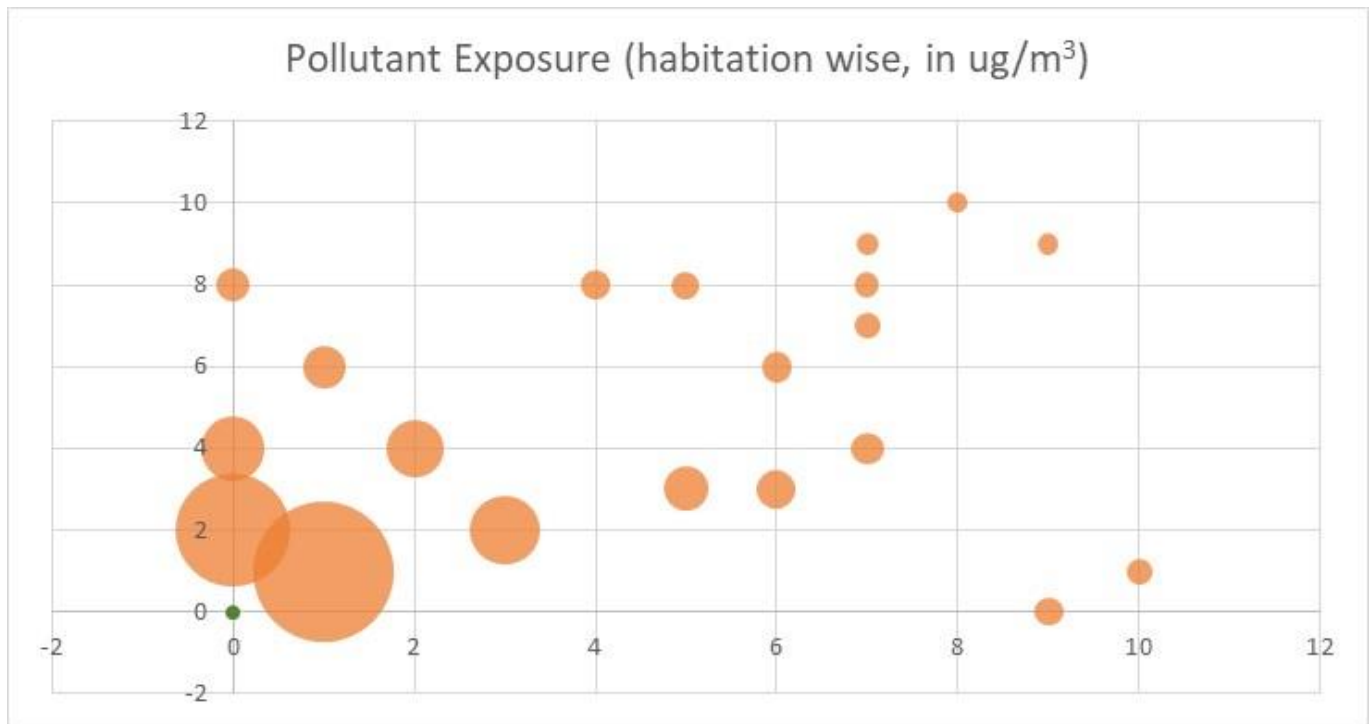


Figure 4: Exposure levels at optimized plant location

VIII. GENERALIZATION OF THE MODEL

The simulation procedure adopted in this study is flexible. Plume Dispersion Models come with their own set of assumptions and pre-requisites. One model cannot be used in all types of environments and geographies. However, it is possible to use this simulation procedure along with other Plume Dispersion Models.

A generalized process to be followed while using a similar simulation procedure is summarized below.

1. Selecting the Plume Dispersion Model to calculate the concentration of pollutants at any given location relative to the location of the power plant.
2. Assigning values to the constants used in the calculation of pollutant concentration depending upon various environmental and territorial factors
3. Selecting a possible location where the plant can be set up.
4. Developing/Selecting a statistic that can be used to measure the externalities associated with setting up a power plant at that location. It should be noted that this statistic is the variable, whose minimization will ultimately determine the location of the power plant. It should be designed in a way, such that it fairly represents the pollutant concentration across all the nearby areas occurring by setting up the plant at that location (the one selected in step 3)
5. Calculating the value of the statistic for every possible location where the plant can be set-up. In other words, repeating step 2 and 3 for all possible locations.
6. Minimizing the statistic

IX. CONCLUSION

Pollutants in the environment due to emission externalities has been a huge problem and the major concern is to counter the confounded risk of emission externalities leading to affecting of public health as well as environmental damage. Here we tried various interventions to reduce greenhouse gases by finding an optimal location with the least WAE. The goal here was to minimise public exposure of harmful emissions. Using operational and emission perspectives we came to a conclusion for a best candidate location for the power plant.

X. LIMITATIONS

The study suffers from the limitations of correct model selection. There are a lot of models that explain Pollution dispersion under multiple conditions. Variables such as wind velocity, temperature of the atmosphere, temperature of the emitted gases, wind direction, rate of gaseous emission, humidity conditions, geographical terrain, vegetative cover and many others affect the concentration of pollutants. The sheer number of variables makes the models complex and sometimes less accurate. The Gaussian Plume distribution model cannot be applied to emissions which have high concentrations of gases that with other constituents of the atmosphere. There can be no decay, oxidation, combustion or any other process that chemically changes the properties of the plume. The occurrence of any of these reactions will result into inaccurate estimation of pollutant concentration through the Gaussian Dispersion model. Furthermore, the accuracy of the estimates reduces when there are a lot of barriers because a part of the particulate matter settles on surfaces of trees, buildings, mountains and even the ground. Occurrences of natural events like rainfall completely distorts the estimates. The chemical properties of the plume and its temperature during emissions determines how high it rises. This has a considerable impact on concentration estimate. Furthermore, the Gaussian Distribution model assumes that winds carry the plume. The model fails

to estimate the impact of common gas dispersion under very low wind conditions.

These limitations can however be overcome by careful selection of the model to calculate plume dispersion. The problems that arise out of conducting simulations is that they can never be done without a software.

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