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Location Optimization of a Coal Power Plant to Balance Coal Supply and Electric Transmission Costs Against Plant's Emission Exposure

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LOCATION OPTIMIZATION OF A COAL POWER PLANT TO BALANCE COAL SUPPLY AND ELECTRIC TRANSMISSION COSTS AGAINST PLANT'S EMISSION EXPOSURE

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Operations Management degree and is acceptable for meeting the thesis proposal requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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CONTENTS

ABBREVIATIONS

CFC- Chloro-Fluro-Carbons

CO_2- Carbon Dioxide

CO- Carbon Monoxide

CRM-Research Center for Chemical Risk Management

EPA- Environmental Protection Agency

GW-Gigawatt

KWH- Kilowatt hours

METI-Ministry of Economy, Trade and Industry

NAAQS- National Ambient Air Quality Standards

NO_2-Nitrogen Dioxide

NO_x- Nitrogen Oxides

PPM- Parts Per Million

$PM_{2.5}$- Particle Matter less than 2.5 microns

PM_{10}- Particle Matter less than 10 microns

SO_2- Sulphur Dioxide

VOC- Volatile Organic Compounds

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ABSTRACT

LOCATION OPTIMIZATION OF A COAL POWER PLANT TO BALANCE COALSUPPLY AND ELECTRIC TRANSMISSION COSTS AGAINST PLANT'S EMISSION EXPOSURE

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This research is focused on developing a location analysis methodology that can minimize the pollutant exposure to the public while ensuring that the combined costs of electric transmission losses and coal logistics are minimized. Coal power plants will provide a critical contribution towards meeting electricity demands for various nations in the foreseeable future. The site selection for a new coal power plant is extremely important from an investment point of view. The operational costs for running a coal power plant can be minimized by a combined emphasis on placing a coal power plant near coal mines as well as customers. However, this business strategy has produced a detrimental effect on the environment in various nations around the globe. In this new era of rapid urbanization, increased electric utility demand and environmental consciousness; the location analysis for a new coal power plant needs to include both the investment and environmental considerations.

To provide a general background of the issue, a detailed literature review was conducted on the topics of Environmental Protection Agency (EPA) pollutant dispersion models, health effects due to exposure to pollutants, coal logistics, electric transmission technical losses, and location analysis models. Next, a methodology, based on dynamic programming, was formulated by combing the EPA's pollutant

dispersion models with the minimum spanning tree algorithm to calculate the combined costs of coal logistics and electric transmission losses for a given set of coal mines and customers present on a network. The subsequent simulation was developed based on the proposed methodology. The simulation successfully proved that the selection of a site on a grid map provided the minimum of the combined cost of electric line losses and coal transportation, and no customers were exposed to pollutant concentration above the declared threshold for that pollutant. The resultant emission's data were validated via comparing against the EPA Screen3 and Japanese Ministry of Economy, Trade, and Industry (METI-LIS) models. The minimum spanning tree for electric transmission lines and coal transportation were validated using R-software.

Chapter 1. Introduction

Electric power generation and transmission generally includes power stations, energy resources, electric grids, utility companies, and consumers. Power stations convert heat extracted from chemical combustion, nuclear fission, and geothermal energy into electricity by the use of generators. In 2017, the Unites States primary source of energy for power generation was fossil fuels, with coal accounting for 30.1% of the total share followed by 31.7% for natural gas and 0.9% for liquid fuels (EIA, 2018). World electric power consumption in 2015 stood at 23.5 trillion kWh with expected growth to 34 trillion kWh by 2040. Currently the world-wide coal usage per annum for electric power generation stands at 3.34 Billion Tons. It is estimated that world-wide coal consumption for electric power generation between 2015-2040 will remain stable, with the United States and China even decreasing their dependence. However, these reductions in usage will be offset by a rapid increase in coal-based power generation in developing countries (EIA, 2017).

Burning of fossil fuels, especially coal, has major consequences on the local environment. Coal upon combustion produces CO_2, SO_2, NO_x, CO, metallic and Particle Matter (PM_{10} & $PM_{2.5}$). The presence of these chemical compounds in the atmosphere in close vicinity to humans, livestock, and agriculture carries detrimental health consequences.

Coal power plants are very expensive investments, with an average investment for a 300 MW plant being greater than $1 billion dollars with an operating life cycle of about 37 years. The biggest expense in coal power plant operations is the fuel and its delivery cost. The delivery of electricity from power plants to consumers requires investment in power lines and transmission grids. A 69 kV overhead single transmission line costs about $285,000 per mile whereas a 138-kV overhead transmission line costs about $390,000 per mile (Alonso & Greenwell, 2013).

A profitable outcome for a financial investment is dependent on the principle of generating higher revenue than the associated costs. The proximity of a coal power plant or multiple power plants near dense population centers makes sense, in terms of lowering electric transmission costs. If a coal mine is in close vicinity it also reduces the operational cost. However, when emissions are taken into consideration, such inclinations have played a key role in worsening health crises in many countries like India and China (Guttikunda & Jawahar, 2014; Xie, Huang, & Qin, 2016).

The amount of emissions from a coal burning plant is directly proportional to the amount of coal usage; the greater the amount of megawatt production of electricity the greater the amount of coal consumed. The chemical composition of emissions produced by burning coal depends on multiple factors, including percentage of ash, Sulphur, Metals, and Carbon content of coal as well as the operating temperature of the boilers. For example, a stoker fired boiler burning one ton of anthracite coal emits 17.67 kg of SO_x, 4.08 kg of NO_x, 0.272 kg of CO, 2574 kg of CO_2, 0.004 kg of Pb, and 0.136 kg of toxic organic compounds (TOC) etc. (Aul & Pechan,1996). The dispersion of emissions in the environment is dependent upon weather conditions, such as wind magnitude and direction, temperature, chemical reactivity of emissions with the atmosphere, emission source height, and local terrain.

In the last two decades, there has been a heightened awareness concerning air pollution, such as smog formation due to Particle Matter ($PM_{2.5}$, PM_{10}) in air, acid rain due to SO_x

and NO_x presence in atmosphere, even increasing global temperature due to increased carbon dioxide emission and ozone depletion as a result of Chloro-Fluro-Carbons (CFC) activity. This alertness has produced the need to balance coal power plant location decisions based on transmission and operational costs with the environmental impact on the local population, keeping profits and environmental consequences balanced.

Statement of Need

Coal power plants use large amount of coal to convert heat energy into electricity. In India from 2010 to 2011, power plants with install capacity of 121 GW consumed 503 million tons of coal. That equates to about 4100 tons of coal burnt for one MW of electricity per year (Guttikunda & Jawahar, 2014). Inefficient coal power burn operations and low grade contaminated coals can result in release of highly toxic elements, such as arsenic, fluorine, selenium, mercury, as well as particle matter such as soot and ash (Finkelman, 2002). With 40.665% of world electric energy demand being met by coal power plants, it is imperative that new coal power spatial placement must be done not only from an economical point of view but also from an environmental point of view (IEA Statistics, 2014).

In 2015, the world's coal-based energy demand per annum stood at 160 quadrillion Btu and at the most optimistic scenario predicted to stay at that peak level for the next 24 years. Figure 1 shows worldwide coal consumption projections from various regions. It indicates that as developed nations like the United States and China try to shift away from coal to cleaner energy resources; developing nations like India and regional countries in Africa are pushing towards greater coal usage. India's net electric generation is predicted to grow at a rate of 3.2%/year from 1250 billion kWh in 2015 to 2750 billion kWh in 2040, with coal representing 62% of the total energy source. China meanwhile is making a great effort to minimize its total exposure to coal based electric power generation (EIA, 2017). By 2040 it would still be producing 4300 billion kWh from coal burn. In the United States and European nations as well as Japan, although they will be making strides towards renewable power generation and cleaner fuels usage, they will still be somewhat dependent upon coal for electric power generation well into 2040 (EIA, 2017). Since the coal usage is strategically irreplaceable and consistent for at least the next 24 years, there is the need to develop a methodology to take into consideration both economic and environmental factors for location decisions of new coal power plants. This methodology should support efficient operations and reduce exposure to the pollution.

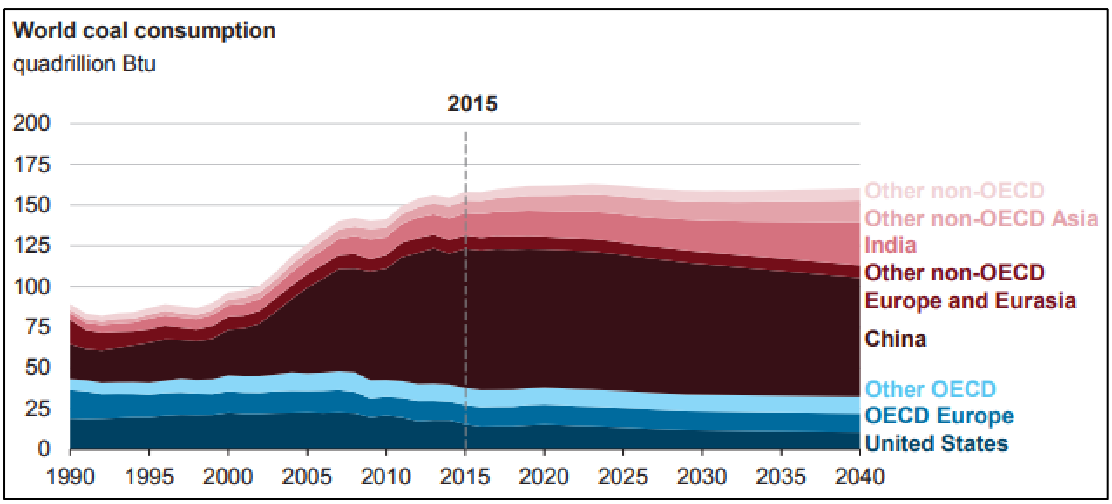

Figure 1. World coal consumption 2015-2040 (EIA, 2017)

Problem of Study

The problem of study is to develop an approach which utilizes the existing location decision techniques and optimization strategies coupled with financial and emission dispersion models, to calculate an optimal location for a new power plant in a certain geographical area that minimizes cost of electric transmission as well as emission interaction with other point source emissions.

Purpose of Study

The purpose of this study is to develop a dynamic program which allows city planners, industrial zone managers, coal power plant owners, and supply chain managers to determine the optimal location for a coal power plant which assures both minimum total costs (production and transmission costs) and environmental impact. The main objectives are:

1. To simulate emission dispersion, from a point source (coal power plant) over a geographical area using a steady state Gaussian dispersion model.
2. To find the shortest network for electric transmission from a coal power plant to the respective sub stations/factories using “minimum spanning tree” algorithms such as Prim’s, Sollin’s or Kruskal’s algorithm. Using Prim’s, Sollin’s or Kruskal’s algorithm to find the shortest distance network between coal power plant and various coal mines.
3. To calculate various transmission costs per change in feasible location of a power plant using a brute force search (every position is analyzed on a map, if search area is small) or metaheuristics such as simulated annealing (random search on a map, if search area is large).
4. To find an optimal location by selecting the minimum cost arrangement that meets the environmental safety criteria.

Research Questions

The intent of algorithm development is to make the decision-making process for final allotment of space for power plants less complex and time consuming. The algorithm covers special topics from the field of operations management, operations research, graph theory, environmental chemistry, and computer sciences. It is imperative that the algorithm delivers accurate information to the intended user to be trustworthy and useful. To check fidelity of the algorithm, the following research questions need to be answered for quality assurance purposes:

1. Which plume dispersion model can be combined with the location optimization algorithm in the proposed dynamic program that results in an optimal plant location, where National Ambient Air Quality Standards (NAAQS) pollutant criteria and operational cost criteria are met?
2. Does the developed dynamic program assure better location for a coal power plant where the cost of coal logistics as well as electric transmission is less, compared to a random pick or a greedy decision?
3. Does the power plant emission foot print for the determined location keeps the pollution factor less than the National Ambient Air Quality Standards (NAAQS) threshold for 95% of the location population?

To answer research question 1, various Environmental Protection Agency (EPA) and foreign agencies pollution dispersion models were studied. Their application in dynamic programming was dependent upon computational cost and time availability. It is the intent that the pollution dispersion model applied is robust enough that the simulated results are no more than 25% different from observed values of other pollution models.

To answer research question 2, in terms of production and transmission costs, the two main components analyzed in our study are:

1. Cost of coal delivery based on distance and load.
2. Electric transmission cost.

Both linear and non-linear programming were used to formulate cost saving optimization strategies. For a given net distance, the cost of electric transmission and coal delivery costs were calculated using formulas from published resources. The intent is to have a difference of no more than 10%.

To answer the research question 3, the contours of plume dispersion under various atmospheric conditions were analyzed against National Ambient Air Quality Standards (NAAQS) chemical pollutant thresholds and population foot prints on a 2-dimensional map. The objective is to limit public exposure to harmful compounds, if concentration is above NAAQS threshold.

Assumptions of the Study

1. Coal power plant emissions are continuous and follow a Gaussian dispersion model with steady state weather conditions.
2. Power plant coal consumption is directly related to the amount of power requirement. Line losses are proportional to distance covered by electricity.
3. The pollutants from exhaust do not undergo any chemical transformation upon interaction with the environment.
4. Target consumers as well as coal mine position on the map remain static.
5. Power input by the power plant on the transmission line is less than power received by consumers (line losses).

Delimitations

The study is delimited to the coal power plants located in the United States due to specific norms and standards regarding the emission pollution. Nevertheless, the developed methodology can be used for other countries after appropriate adjustments.

Limitations

1. Currently the range of emission modeling is for a 100 km x 100 km grid. Certain sophisticated modelers can model transcontinental emission dispersion. Due to limited time and resources, this is beyond of scope of the current thesis.
2. The transmission line and coal delivery pathways are built using a minimum spanning tree between vertices. However, the cost of a tree can be further reduced by using a 'Steiner' tree which allows intermediate connections points (Skiena, 2008). Nevertheless, due to coding complexity and Nondeterministic Polynomial Time (NP) nature of the Steiner tree that approach has not been pursued.
3. Building downwash has not been considered due to time and complexity.
4. Constant 90-degree East wind direction has been assumed on all models. This is to control the complexity faced in integrating the plume interaction detection with the Cartesian coordinate system.
5. The model does not take into consideration deviation in plume dispersion due to any urban growth caused by installation of a new power plant.

In the next chapter a detailed literature review is provided which focuses on the background of various atmospheric dispersion models, health risks posed by various pollutants, the cost of coal transport, electric transmission losses, and location analysis strategies.

Chapter 2. Literature Review

Introduction

In the 21st century the issue of environmental awareness has been on the rise. Various studies and methodologies have been published which attempted to quantify the distribution of emissions of a coal power plant over a geographical area. The attempts to study and mitigate pollution impact on local environment, to gauge estimated exposure of chemical compounds on the public which present in the trail wind of these emissions, and to study consequential health impacts were the primary key drivers for accurate simulation of these emissions. Optimization is a part of mathematical sciences which focuses on driving an objective function to a position of maximization or minimization under various constraints. Multi-attribute decision making looks at various contradictory relationships between input variables to find the best compromise. Many research and published studies covered various aspects of coal power plant investment and operational decisions under the umbrella of optimization and multi-criteria decision making.

Atmospheric Dispersion Model

The Environmental Protection Agency (EPA), as a part of their mission to protect human health and environment, has made significant contributions in development of various atmospheric models. These models take inputs like meteorological conditions, emission rates, and stack heights to simulate emitted matter's dispersion and chemical reactions in the atmosphere. Regulation agencies use these models in permitting processes, determining additional control requirements, predicting future concentrations in atmosphere from multiple resources and characterization of primary and secondary pollutants (EPA 2016).

The EPA has recommended AERMOD and CALPUFF modeling systems for state implementation plans, new source review and prevention of significant deterioration programs. AEROMOD is a steady state plume modeler that measures pollutant dispersion, based upon characteristics of the surface boundary layer, the convective boundary layer and the planetary boundary layer, coupled with terrain characteristics and meteorological conditions. CALPUFF is a non-steady state model that measures pollutant dispersion and transformation over long range distances under ever changing spatial and time varying meteorological conditions as well as complex terrain. Other recommended models published are BLP, CALINE3, CAL3QHC/CAL3QHCR, CTDMPLUS, and OCD (EPA, 2016). BLP is based upon a Gaussian plume dispersion model associated with modeling industrial sources where plume rise and downwash effects are important from point sources. CALINE3 is a steady state Gaussian plume dispersion model for air pollution dispersion at receptor locations. CTDMPLUS is a Gaussian air quality model for stable meteorological conditions and complex terrain. A group of alternative models are also presented by the EPA, which can be applied on a case by case basis with proper reasoning. These include ADAM, ADMS-3, AFTOX, ASPEN, DEGADIS, HGSYSTEM, HOTMAC/ RAPTAD, HYROAD, ISC3, ISC-Prime, OBODM, OZIPR, Panache, PLUVUEII, SCIPUFF, SDM, and SLAB. ADMS-3 is an advanced dispersion model for calculating pollutant dispersion from point, line, volume, and area sources. The sophisticated platform incorporates varying metrological conditions, radioactive-decay, complex terrain, wet deposition, and gravitational effects, etc. for pollutant dispersion and decay. AFTOX uses a Gaussian dispersion model which handles continuous or instantaneous gas or liquid release from a point or area source. ISC3 is a steady state

Gaussian model which calculates pollutant dispersion associated with an industrial complex. PLUVUEII is used for estimating visual range reduction and atmospheric discolorations from particle matter and nitrogen oxides emissions (EPA,2016).

Kaw Nation Environmental Agency in Kaw City, Oklahoma used the AEROMOD modeler to estimate the concentration of SO_2 and PM originating from various stationary resources in Noble County, entering tribal lands. The source sites selected for input included various refineries, power plants, and coke production plants. One of the coal power plants used in the study had the following characteristics: stack height of 152.44 m, diameter of 6.1 m, SO_2 emission rate of 407.73 lb/hour, Particle Matter emission rate of 43.16 lb/hour, and exhaust temperature of 402 Kelvin. The net concentration of emissions at the coal power plant accounted to about 16 ug/m^3 of Particle Matter and 205 ug/m^3 of SO_2. The dispersion of these emissions was affected by stack height, terrain, wind direction and turbulence, horizontal distance, and various metrological conditions. In total 21% of these emissions reached the tribal area and this value fluctuated between winter and summer season (Alemayehu & Hackett, 2015). See Figures 2 and 3 for the AERMOD distribution map of SO_2 and Particle Matter.

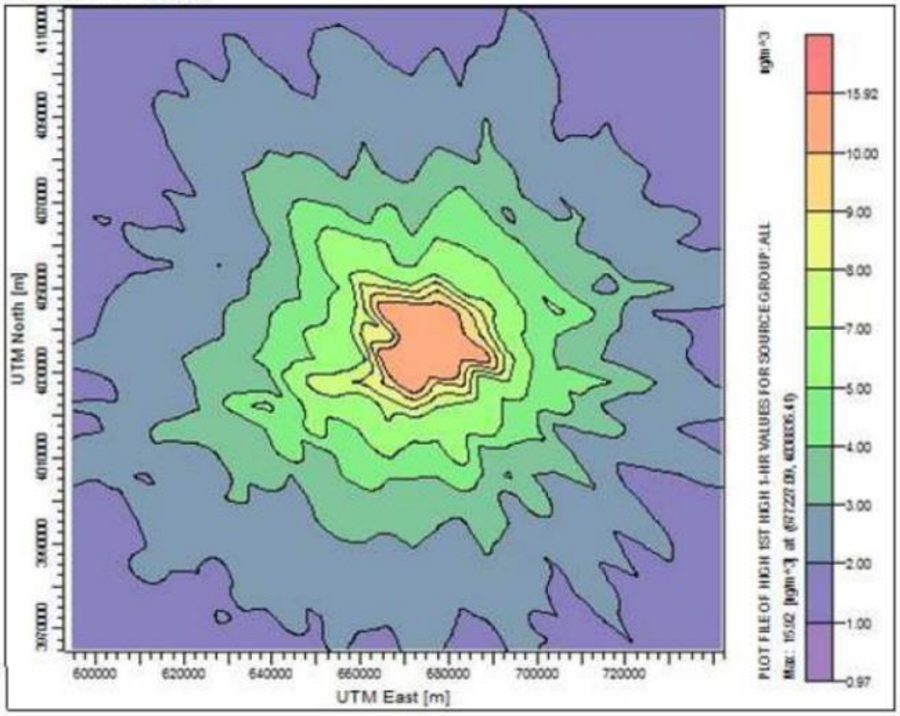

Figure 2. Distributed concentration of Particle Matter from coal power plant *(Alemayehu & Hackett, 2015)*

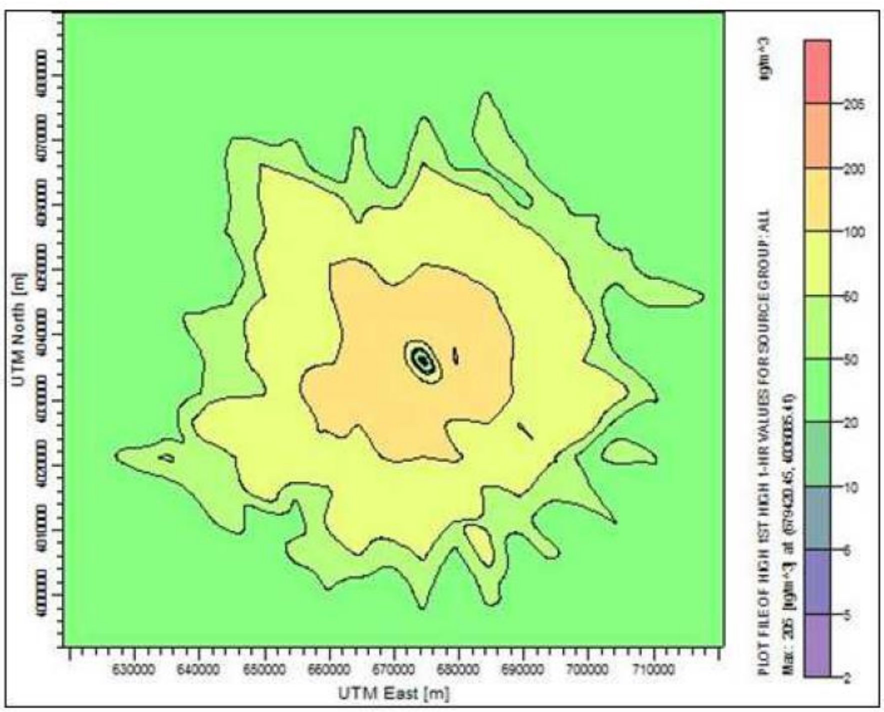

Figure 3. Distributed concentration of SO_2 from coal power plant *(Alemayehu & Hackett, 2015)*

The issue of accurate modeling of emissions has also gained attention in Japan, where models like the AIST-ADMER and METI-LIS have been developed for emission studies. The AIST-ADMER model by the National Institute of Advanced Industrial Science and Technology incorporates metrological data and emission characteristics to calculate the average distribution of chemical concentration and exposure of general population over a wide area. METI-LIS, developed by Ministry of Economy, Trade, and Industry, emphasizes calculation of pollutant distribution released from lower and elevated sources under fixed and dynamic meteorological conditions. Razi (2012) used the AIST-ADMER model to estimate regional concentration and distribution of mercury in the central region of Honshu Island, home to various medium and heavy scale industries in Japan. The METI-LIS modeler was then used to study mercury distribution and concentration in close vicinity to industrial zones which is released from two hypothetical coal power plants set 20 km apart. In Japan, mercury is considered a hazardous carcinogenic air pollutant, with the maximum annual mean air quality level set at 0.04 ug/m^3. Coal burning power plants have been identified as one of the key sources of atmospheric emissions of mercury in the atmosphere. A 1000 MW power plant, consuming about 390 tons of coal per hour can release up to 42.6 kg of mercury in the atmosphere per year. Key findings from the METI-LIS study showed mercury concentration in the simulated area ranged between 0.0068-0.0118 ug/m^3 in winter time and 0.0028-0.0068 ug/m^3 in summer time. The model established that certain people located close to the emission source will be exposed to a higher level of mercury compared to the general population, but the exposure will not exceed the 0.04ug/m^3 level (Razi & Hiroshi, 2012). The study did not pursue the effect of testing multiple potential spatial sites where concentration, distribution, and interaction of emitted mercury could have been further minimized.

The issue of accurate prediction of emissions has also gained traction in India, where 70% of electricity is generated from coal. Varma (2014) used the general Gaussian plume equation with various Pasquill-Gifford Stability classes, to determine concentration of SO_2, NO_x, CO and Particle Matter emitted from Rayalaseema Thermal Project, at various grid points. The Rayalaseema Thermal Project is a 1050 MW power plant consuming 685 tons of coal per hour. The stack height used for the study is 220 m from ground level. Emission rates used for the study were 1094 g of SO_2 per second, 69.3 g of NO_x per second, 3.6 g of CO per second, and 164 g of Particle Matter per second. Receptor points chosen for concentration down range were located at 5 km, 10 km, 15 km, 20 km, 25 km, and 30 km from the point source. Key findings published that concentration of suspended Particle Matter, SO_2, and CO at five kilometers grid point were greater, while NO_x was less than air quality standard. It was further recognized that SO_2 concentration was higher at all grid points and its reduction needed further attention (Varma & Srimurali, 2014). The study had several limitations such as being 1-dimensional, using continuous source emission, no factoring of complex terrain and local weather.

Ill-advised spatial placement of a coal power plant can carry severe consequences for the environment and public. Contradictory weather patterns over land can result in co-joining of emissions from multiple power plants, which can drive distributed concentration of Particle Matter, SO_2, and NO_x above the normal air quality limit. According to Guttikunda (2014), between 2010 and 2011, 503 million tons of coal were used to generate 121 GW of electricity. Estimated emissions due to coal consumption at this rate resulted in 580,000 tons of Particle Matter ($PM_{2.5}$), 100,000 tons of SO_2, 2000,000 tons of NO_x, 1,100,000 tons of CO, and 100,000 tons of volatile organic matter. Resultant exposure of these emissions bore 20 million asthma cases, 80,000-115,000 premature deaths, and a cost to the public and government of India between 3.2 and 4.6 billion dollars. The study used the ENVIRON-Comprehensive air quality model with extensions for integrated assessment of gaseous and particle air pollution over an estimated geographical area of 24.52 million square kilometers and vertical height of 12 km (Guttikunda & Jawahar, 2014). Estimated emissions had a +/- 20% error due to non-uniform emissions reporting, operating conditions, and coal consumption rates. The key findings presented in the study were:

1. Plants with generational capacity of less than 210 MW have emission thresholds set at 350 mg/Nm^3, while those greater than 210 MW have emission thresholds set at 150 mg/Nm^3. Since these emission restrictions are set on boiler size, it is discovered that various power plants with high generational capacities (> 1000 MW) are complying with less stringent emission thresholds (350 mg/Nm^3) by installing boilers with individual capacities being less than 210 MW.
2. The chemical composition of flue-gas, fly ash, and bottom ash showed presence of various metal compounds, such as zinc (1-7%), copper (2-7%), manganese (5-8%), cobalt (7-10%), cadmium (12-18%), selenium (60-70%), mercury (70-80%), and trace amounts of lead and iron. Between 30-40% of particle matter pollution is secondary in nature, due to SO_2 conversion to aerial sulfates.

3. There are no regulations on control of NO_x compounds in India, which power plants represent 30% of total releases in environment.
4. Current environmental regulation assessment for coal power plants is done up to 50 km from the point source, however it has been observed that emissions especially from high stacks can be detected up to 200 to 400 km away, depending upon the wind conditions.
5. There is a very strong correlation between clustering of power plants and high emissions concentration in local and intermediate geographical areas. Most coal plants are built near coal mines, irrespective of the fact that major population centers are in the immediate vicinity. Examples include Kobra cluster, Mundra cluster, and Mumbai cluster where population density can vary from 1000/km^2 to 10,000/km^2 (Guttikunda & Jawahar, 2014).

This study was extremely helpful as it established a direct link between spatial placement of multiple coal power plants only from the financial point of view such as being close to coal mines to reduce transportation cost and multiple units operating in a small area to share company resources and commitment to minimum air quality standards. Nevertheless, it leads to worsening pollution crises due to a high level of emissions, conversion of various emissions into secondary pollutants and emission interactions. The study has also provided a mathematical relationship between particle matter concentrations and mortality rate.

NO_x derivatives like nitrogen dioxide, nitric acid, nitrates, nitric oxide, and nitrous oxide carry a wide range of environmental and health consequences. Nitrogen is an inert element which does not react with oxygen under ambient conditions. However, under extreme temperatures such as that of a boiler at a coal power plant, nitrogen molecules N_2, can break down to form elemental ‘N’ and react with oxygen, creating NO_x compounds. NO_x reacts with volatile organic matter in presence of sunlight to form smog. NO_x with SO_2 in the upper atmosphere can react with water vapor and condense in the form of acidic rain. Nitrate laden particles and nitrogen dioxide are responsible for a reddish-brownish hue in urban cities and national parks. NO_x compounds exposure to humans has resulted in asthma, emphysema, bronchitis, damage to lung tissue, decreased performance of lungs, aggravated heart condition, and premature deaths. NO_x radicals like the nitrate radical, nitroarenes, and nitrosamines have the potential to cause biological mutations (EPA, 1998). Gourgue (2015) developed a model to study dispersion of NO_x compounds released from a power plant. The methodology used a general Gaussian pollutant dispersion equation in combination with Holland’s equation, which accounts for an ultimate increase in plume height due to plume buoyancy as well as convective airflow. It was recognized that plume dispersion was affected by hilly terrain as well as land sea boundaries. Natural barriers created by hilly terrain and wind patterns from the ocean drove NO_x emission concentration to as high as 140 ug/m^3 in some areas (Gourgue, Aharoune, & Ihlal, 2015). The study was indeed helpful to get an understanding of nitrogen oxides concentration under different metrological conditions and emission rates. However, the study failed to compare simulation data against actual readings from monitoring stations. Also, the study failed to mention power plant type and the emission used at the point source in the simulation.

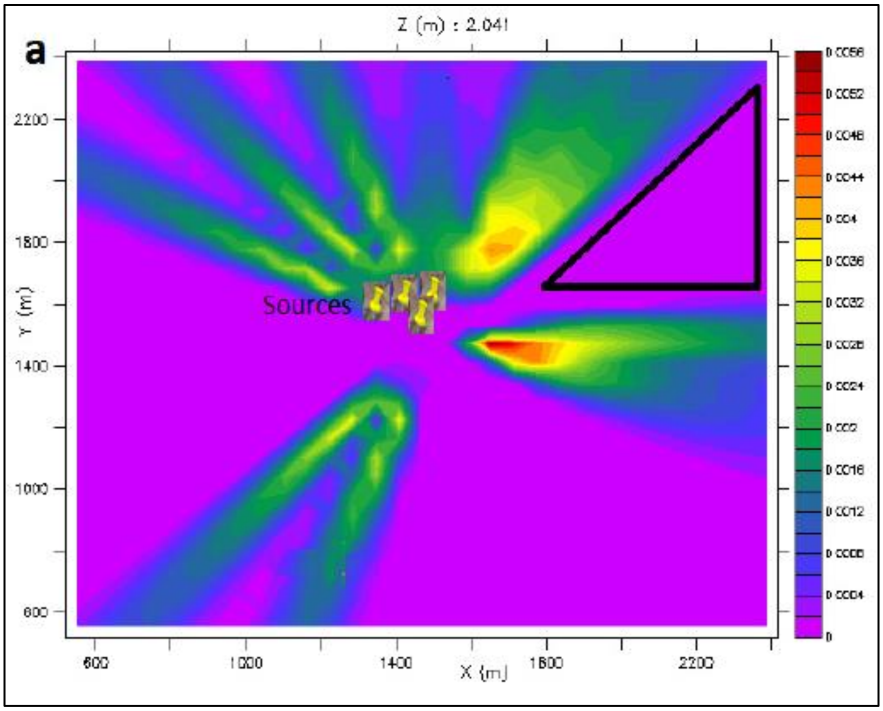

Figure 4. NO_x simulated dispersion from CIBELL II Boilers *(Gourgue, Aharoune, & Ihlal, 2015)*

Weather and terrain have a significant impact on dispersion of pollutants. In cold weather, the phenomena of temperature inversion can significantly impact air quality in a very short duration of time. An inversion condition happens when stable and cooler air near the Earth surface is followed by a layer of warmer air, just above. Due to extremely low mixing and dispersion activity, the pollutants can linger in this layer for a very long time, as shown in Figure 5 (Heritage Protection, 2013). Tran and Mölders (2012), from University of Alaska, analyzed contribution of Particle Matter ($PM_{2.5}$) from point emission sources to the near surface air layer in certain areas in Fairbanks, AK, where air quality is worse than National Ambient Air Quality Standards (NAAQS), aka "Non-Attainment Areas". It has been often observed that Fairbanks, AK, being extremely cold in winter creates a phenomenon of an inversion layer which results in formation of non-attainment areas (Tran & Mölders, 2012).

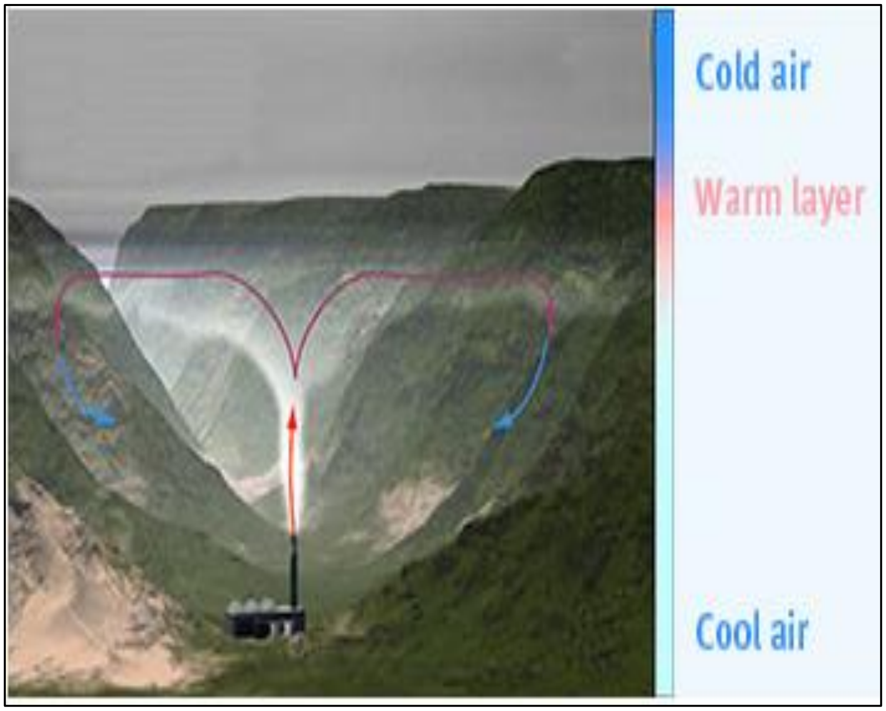

Figure 5. Inversion layer *(Heritage Protection, 2013)*

In 2006, the National Ambient Air Quality Standards (NAAQS) tightened the criteria for Particle Matter ($PM_{2.5}$) concentration for 24-hour period to less than 35 ug/m^3, which required a push for development of strategies for further emissions control. Since emissions control is an expensive investment, a statistical study was done to investigate if the emissions from the point source have a significant contribution in non-attainment areas. The conclusion of the study was as follows: Particle Matter ($PM_{2.5}$) concentration was high at breathing level very close to the point source, but emissions from point sources had a very minor contribution on Particle Matter ($PM_{2.5}$) in non-attainment areas. Wind speed, temperature, and mixing heights have a strong influence on the Particle Matter's ($PM_{2.5}$) ability to stay or leave a non-attainment area. Particle Matter ($PM_{2.5}$) dispersion from a point source can reach up to 16 km, depending upon stack height, wind speed, and presence of an inversion layer above the height of emission. Nonpoint source emissions are major contributors of Particle Matter ($PM_{2.5}$) in non-attainment areas, and investment in emission controls at point sources would not guarantee any significant reduction of Particle Matter ($PM_{2.5}$) in non-attainment zones (Tran & Mölders, 2012). The study is a perfect example of using environmental pollution models with statistical analysis to justify a financial cost. Since a financial investment decision would not yield any major benefit in terms of reducing impact on environment, a company can save that money for future use.

We have now discussed the coal power plant involvement as a point source emitter of various pollutants. We have also discussed different modeling techniques which simulate dispersion of emitted pollutants over a wide geographical area, under various meteorological conditions. Due to commonality of Gaussian Plume Dispersion in various industrial plume dispersion modelers, as well as its robust simplistic equation, we have also decided to use it in our methodology.

$$\partial C \frac{\partial C}{\partial t} + div(CV) = \nabla(K\nabla C) + R_i + Q\delta(t - t_0)\delta(x - x_0)\delta(y - y_0)\delta(z - z_0) \qquad (1)$$

The Gaussian plume dispersion equation is based upon the advective-diffusive equation (Equation 1) which explains transfer and diffusion of pollutants from instantaneous sources. Under continuous emission, wind velocity, and turbulent diffusivity, the advective-diffusive equation transforms into the Gaussian plume dispersion equation[1] (Awasthi, Khare, & Gargava, 2006). The Gaussian plume model is a

[1] See **Data Analysis** portion for Gaussian Plume Dispersion equation.

steady state model, due to the emission rate remaining continuous. However, a time dependent puff model is used for non-continuous emissions with varying wind direction and velocity. To account for the impact of air turbulence on distribution of airborne contaminants, dispersion coefficients from Pasquill-Gifford-Turner's six stability classes (A-F) are used with the Gaussian plume dispersion equation; See appendix I & 2. Stability is a qualitative atmospheric character, which governs the vertical motion of the air tract. In an unstable atmosphere, the turbulence is positive (high), while in neutral atmosphere it is zero, and in a stable atmosphere it is suppressed.

Health Impact

The Union of Concerned Scientists based out of Cambridge, MA considers coal power plants as the main contributor of carbon dioxide in the atmosphere. A typical coal power plant of 600 MW can introduce up to 3.5 million tons of CO_2 into the atmosphere each year. On the same note an uncontrolled power plant can emit up to 14,100 tons of SO_2 10,300 tons of NO_x, 220 tons of volatile organic matter (VOC), 720 tons of CO, 220 lb of arsenic, 170 lb of mercury, 114 lb of lead, and four pounds of cadmium (Union of Concerned Scientists, 2017) A case study published by Green Peace Research Labs, Exeter UK on 'Hazardous Emissions from Philippine Coal-fired Power Plants' also mentions the presence of Chromium, Cobalt, Zinc, Nickel, and Copper in fly ash from the Sual, Mauban, and Masinloc coal power plants (Brigden & Santillo, 2002). Per the Environmental Protection Agency (EPA), when it comes to atmospheric pollution, power plants in general are responsible for 50% Mercury, 22% Chromium, 62% Arsenic, 28% Nickel, 60% SO_2, 77% Acidic Rain, and 13% NO_x emissions (EPA, 2017).

The current concentration of Carbon Dioxide (CO_2) in ambient air is about 370 PPM or 0.037% of atmospheric composition. CO_2 is a colorless, odorless gas with a density of 1.98 kg/m^3, making it heavier than air. At concentrations of 2%, CO_2 can cause nausea, headache, confusion, high breathing, and blood pressure. Above 8% concentration CO_2 induces vomiting, asphyxia and can potentially prove lethal. CO_2 reaction with water vapor yields the formation of carbonic acid, which can cause eye irritation upon contact (Universal Industrial Gases. Inc, 2015). The National Ambient Air Quality Standard (NAAQS) has set the exposure limit of Carbon Monoxide (CO) at 9 PPM for eight hours and 35 PPM for one hour (EPA, 2016). CO is also a colorless, odorless and lighter than air gas. CO interaction with hemoglobin, results in reduced efficiency for hemoglobin to transfer oxygen. Exposure to CO results in headache, dizziness, vomiting, nausea, unconsciousness, and death (Harvard Health Publishing, 2013). The National Ambient Air Quality Standards (NAAQS) have set the exposure limit of Sulfur Dioxide (SO_2) to 0.075 PPM for one hour and 0.5PPM for 3-hour exposure. SO_2 is a colorless, pungent odor gas with density heavier than air. Due to its presence in air for up to 3-5 days, it can travel large distances. Exposure to SO_2 can result in lung inflammation, eye irritation, corneal haze, chronic bronchitis, asthma, and heart failure (Ambiente, 2010). The National Ambient Air Quality Standards (NAAQS) have set the annual exposure limit of Nitrogen Dioxide (NO_2) to 0.053 PPM and 100 PPB for one-hour exposure. NO_2 is a yellowish-brownish color gas with a pungent order. It is slightly heavier than air. NIOSH short term exposure limit (STEL) for NO_2 is set at 1 PPM for 15 minutes (Airgas, 2015). NO_2 exposure in humans, results in bronchitis, flu, coughing, respiratory inflammation, and decreased lung function (Department of the Environment and Heritage, 2005).

Arsenic is an odorless and tasteless, naturally accruing grey color metal. Its ambient concentration is about 2 ng/m^3, while National Ambient Air Quality Standards (NIOSH) has set recommended upper exposure limit of 2 ug/m^3 for a 15-minute exposure (EPA, 2018). Continued exposure to arsenic through inhalation or skin contact can cause skin and mucus irritation, hyper skin pigmentation, lung cancer, skin cancer, and bladder cancer (Geiger & Cooper, 2010). Lead is a bluish-grayish metal which Environmental Protection Agency (EPA) classifies as a probable carcinogen. The National Ambient Air Quality Standards (NAAQS) have set exposure limit of lead in suspended particle matter at 0.15 ug/m^3 for a period of no longer than 3 months. Lead exposure can lead to blood, kidney, and neurological disorder. It is also seen to impair hearing, impede Vitamin D metabolism, cause spontaneous abortion, decreases sperm count and slow cognitive and growth rate in children (Geiger & Cooper, 2010). Mercury is a greyish metal found in liquid state at room temperature. Its global ambient concentration in atmosphere is 1.5-2 ng/m^3, however close to industrial zones it can increase up to 41ng/m^3. Exposure to mercury creates serious health consequences, such as nausea, blindness, alteration to testicular tissues, kidney damage, and cerebral palsy. Methyl and organic mercury have also been classified as possible carcinogens by the Environmental Protection Agency (EPA) (Geiger & Cooper, 2010). Chromium (V1) is considered a group A carcinogen. The average concentration of chromium in ambient atmosphere is about 3 ng/m^3 in cities, however close to a chromate facility it can rise as much as 5,500 ng/m^3. Almost all types of coal have certain concentration of chromium. For example, unwashed North Dakota lignite has a mean chromium concentration of 7.5 PPM while that of Texas lignite, it is 20.4 PPM (EPA, 1984). Chromium exposure can result in respiratory, liver, kidney, gastrointestinal, and immune system complications. Cobalt average concentration in atmosphere is about 0.4 ng/m^3, however near one industrial zone it has been reported to be high as 610 ng/m^3. High level exposure to cobalt can result in respiratory, cardiac, and kidney complications. Metals like Nickel with ambient concentration range from 3-30 ng/m^3, which upon significant exposure can also result in respiratory and nasal complications. The Environmental Protection Agency (EPA) has listed Nickel dust as a potential carcinogen (Geiger & Cooper, 2010).

The distribution of organic, inorganic, and metallic compounds in coal power plant emissions depend upon a multitude of factors, such as coal type, operating temperature of the boiler, the age of the equipment, as well as the processing of the coal before the burn. Due to limitations of time, we only presented a handful of chemical compounds as well as the health risk they pose on the public. The message however is quite clear: coal power spatial positioning needs to be done with utmost care so populations living down range of the emissions pathway do not have to suffer.

Coal Transportation

Transportation is a delivery of a product from point A to point B. Delivery can be accomplished using a combination of land, sea, and air routes. Factors influencing the choice of route are minimum cost, distance, and time. Coal power plant operations are quite expensive. The biggest expense in a coal power plant operation is the raw material. About 0.5 tons (428 kg) of coal are used to generate one megawatt of electricity per hour (EIA, 2016). Per the US Energy Information Administration, the average price of coal in 2015 was $29.20 per ton. Upon decomposition of coal expense, it is observed that coal transportation makes up the biggest expense. Total delivery cost in 2014, for a ton of coal stood around $18.53/ ton (EIA, 2016). That equates to about 39% of total raw material expenses. About 70% of all or partial coal transportation from a mine to a power plant uses rail-roads. See Figures 6 and 7 for nominal transportation cost per mile for coal from year 2001 to 2008 (EIA, 2012).

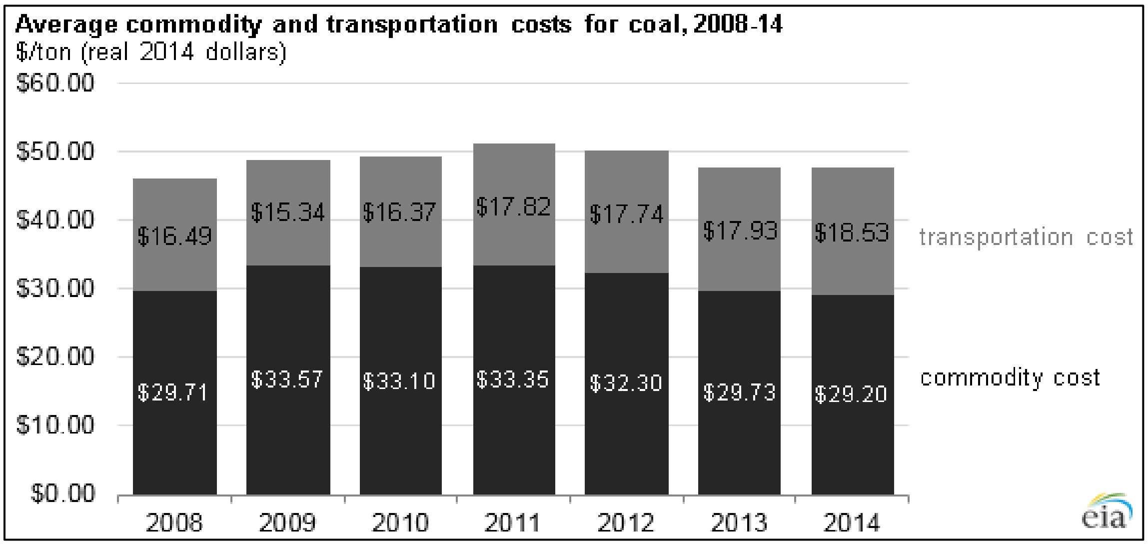

*Figure 6.*Average coal commodity and transportation cost *(EIA, 2016)*

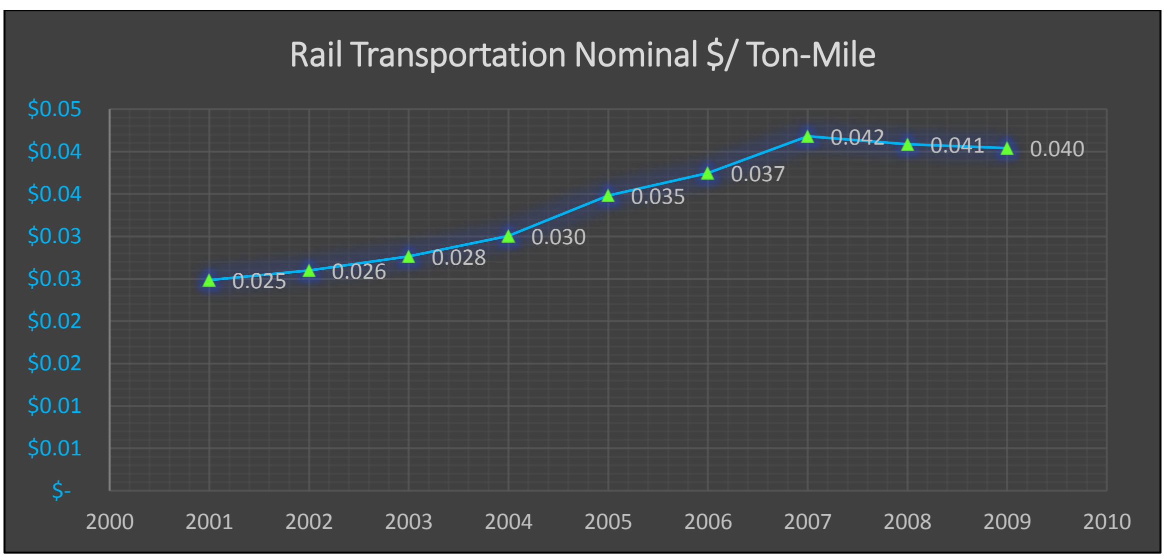

Figure 7. Railroad transportation nominal cost per mile per ton *(EIA, 2012)*

The cost of coal logistics thus plays a critical role in determining the feasibility of operating a coal power plant. In some cases, the cost of coal logistics can often be more expensive than mining of coal and to lower transportation costs, coal power plants are often built near coal mines (EIA, 2017). It is imperative from a financial stand point that a coal power plant which is consuming tons of coal per hour be located near a coal mine to minimize the operational cost.

Electric Transmission Losses

Electric transmission from a power plant to regional sub-station is done using high voltage lines with ratings on these lines in the range from 132 kV to 755 kV. Electric distribution to local consumers enacts after high kV is stepped down to at most 132 kV at a regional substation. A single regional sub-station can serve up to 200 houses in urban areas (Bond, Sims, & Dent, 2013). In total transmission losses account for 17% of total electric distribution losses from power plant to consumers. Technical losses in transmission are categorized in terms of permanent and variable losses. Permanent technical losses range between 25% and 33% on distribution networks. Example of these losses includes corona losses, dielectric losses, open circuit losses, and leakage current losses, etc. Technical variable losses are proportionate to the square of current in a given network. Examples of these losses are impedance losses, losses due to contact resistance, and Joule losses per voltage level, etc. (Bhatti & Haq, 2015).

Corona Losses

Corona losses occur in high voltage transmission lines due to ionization of air present, close to the conductor's surface. The phenomena of Corona discharge is composed of a cumulative ionization process. When air present closed to a transmission line is exposed to a potential gradient of 30 kV per centimeter, it causes free electrons in air to gain enough kinetic energy to knock electrons out from surrounding neutral molecules (Study Electrical, 2017). The phenomena of a corona is usually accompanied by a hissing sound and faint violet glow around transmission lines as demonstrated in Figure. 8 (Electrical Technology, 2018). Production of these ions extract energy from the transmission supply and thus contribute to net electrical losses (Tonmitr, Ratanabuntha, Tonmitr, & Kaneko, 2016). Factors that affect corona losses are atmosphere, conductor size, and spacing between conductors and line voltage. Corona losses above disruptive voltage is quantified using formula 2:

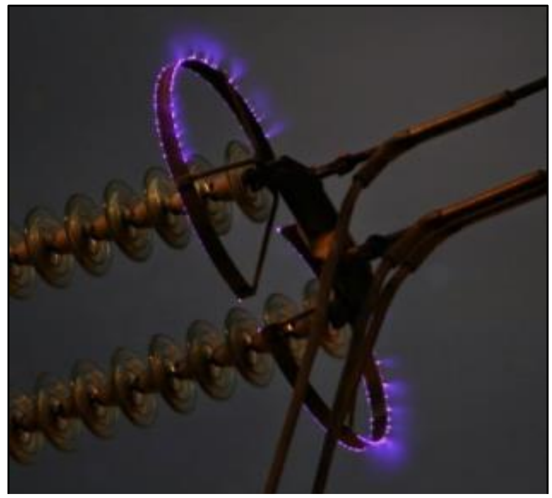

Figure 8. Faint violet glow due to corona effect *(Electrical Technology, 2018)*

$$P_c = \frac{212.4}{\delta} (f+25)(V_p - U_c)^2 \sqrt{\frac{r}{d}} \times 10^{-5} \quad (2)$$

Where; *Pc = power loss, Vp = phase to neutral voltage, Uc = disruptive critical voltage, f = supply frequency, r is radius of transmission line and sigma is density of air.*

Ohmic Losses

Ohmic loss is heat generated by a wire due to its resistance to the flow of current. Magnitude of ohmic loss is directly proportional to the length of the transmission line (m), wire resistance (ohm/m) and square of electric current (A) (Wong, 2011).

The losses described in this section were incorporated in the simulation model due to finance factor. The line losses can cost both the consumer and producer valuable capital over time, and since these losses are proximity based the best way to mitigate these losses is to optimally place a power plant near high demand customers.

Location Analysis

Location analysis refers to modeling of the class of problems best designated as deployment of facilities in a provided space. Location analysis includes four parts:

1. Customers
2. Facilities
3. Space between customer and facilities
4. Metric of either distance or time between customer and facilities

Distances between the facility and customers can be calculated using rectilinear, Euclidean, or Chebyshev principles (Revelle & Eiselt, 2005). In a network setting, distance between two points, present on the network, is typically calculated using the shortest route from a set of given arcs. Classes of location objectives can be as follow:

- Pull Problem *(The objective function desires on minimizing the proximity between facilities and customer)*
- Capture Problem *(The facility imbeds the cost of transportation in the commodity prices)*
- Push Problem *(The objective function desires maximizing the distances between facilities and customer)*
- Equity *(Attempt to have similar distances between multiple facilities and the customer)*
- Free Entry Problem *(A facility location problem that minimizes the sum of plant opening costs and distribution costs whereas the total number of facilities is calculated as consequence of minimum cost solution)*
- Least set cover problems (Revelle & Eiselt, 2005)

In a single facility setup, the ultimate objective of location analysis is to find a "point" on a planer grid which minimizes the sum of total transportation cost[2] to several customers. This objective problem can be represented by the Center of Gravity approach. The Center of gravity approach provide a candidate x and y coordinate solution for setting up a new facility that provides the lowest total transport cost. The Center of gravity approach, however, does not take into consideration the real-life constraints. For example, the distances between facility and customers may be taken as straight-line distances whereas a path from point A to point B may be best represented by a network. They do not consider the volatility in set up costs associated with various possible locations. The

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[2] Total transportation cost - Product size x transportation rate to ship to the individual customer x distance the customer

volume of product flow assigned to each customer is represented by a static value, whereas the product demand may be subject to trend or seasonality (Ballou, 2004).

Another tool for facility location problem solving is mixed integer linear programming. In mixed integer linear programming the decision variables are constrained to be in integer values at an optimal solution. The mixed integer linear programming is considered non-convex problems, which can be solved using a Branch and Bound technique (Frontline Systems Inc., 2012). Mixed integer linear programming has the capability to optimally deal with the issue of fixed cost while insuring that customer demand is met on a given network. The new location for a facility can be best expressed with an objective function that minimizes the fixed and linear variable costs to transfer all products from facility to customers under various numbers of constraints. With increased number of constraints, the mixed integer linear programming can be highly exhaustive in terms of computational demand and an optimal solution is not always guaranteed (Ballou, 2004).

If optimality is not the core requirement when searching for a new location, heuristic methods can provide a sub-optimal solution within a reasonable processing time. Other location search techniques are guided linear programming, dynamic warehouse location, the spatial interaction model, and multi criteria decision analysis.

In this research we plan to use combination of ‘push’ and ‘pull’ location analysis strategy to calculate transmission losses and coal logistics cost, with distances between power plant and stakeholders best represented by a network. The pull strategy will focus on finding a location, where the combined cost of electric transmission losses and coal delivery can be minimized. The pull strategy is suitable for this case, since its main objective is to reduce the distance between customers and supplier. However, in our research, the objective function aims to minimize the combined electric transmission and coal logistics cost using a unit cost weight per length. This approach will ensure that on a given network the coal power plant is located closest to the chief electric customer. The same idea will apply to a coal mine providing the highest percentage of coal to power plant.

The push strategy will focus on minimizing emission exposure by maximizing distances between power plant and customers. The push strategy is suitable in this case since its main objective is to drive as much reasonable distance as possible, between coal power plant and customer. The push strategy will be combined with binary decision making to allocate the maximum distance between emission source and customer such that the pollutant exposure to that customers is less than NIOSH threshold for that pollutant. The maximum separation that can be achieved however, is governed by the downwind range of Gaussian plume dispersion model[3].

Summary

The prosperity and health of a society is closely inter-linked to the condition of its surrounding environment. Recent growth in human population has increased the demand for electricity. Investments in coal power plants are pursued due to already well-developed technology regarding efficient coal burn for high energy extraction, comparatively cheap and vast supply of coal, and no constraints due to daily weather and planetary cycles. However, on the flip side of this advantage, the high level of emissions from coal power plants wreak havoc on the local environment. Emission dispersion from

[3] The current downwind range is limited to 20 km.

a coal power plant is affected by local terrain, weather conditions, exhaust rate as well as the height of the stack. Many pollutant dispersion models are available to simulate the extent of dispersion of emitted matter in the environment. Site selection can make a huge difference in keeping pollutant concentration below the National Ambient Air Quality Standards (NAAQS) threshold or site selection can further exacerbate, already poor environmental conditions. From an investment point of view, a coal power plant site selection is ideal near the coal mine to minimize cost of coal delivery, near existing coal power plants to share human resource capability as well as lowering overhead capital investment, near cities and factories to lower capital investment, maintenance, and technical losses of transmission infrastructure. However, this one-sided approach has already plunged many major cities around the world into the depths of the worst air quality like New Delhi and Beijing, etc. The solution to the problem is to balance profit with environmental health concerns, by using multi-criteria decision analysis for coal power plant site selection. Per the conducted literature review not a single paper has been found, which combines non-linear programming methodology, plume dispersion models, effect of electric transmission losses, and coal logistics to come up with a better coal power plant site selection program, which can minimize exposure of emitted pollutants to a large percentage of the population and ensure feasible operating costs. As mentioned in the atmospheric dispersion model section, this study will use a Gaussian Plume Dispersion equation for estimation of chemical dispersion from the point source. In terms of electric distribution modeling this study will first use a minimum spanning tree algorithm to find the minimum length transmission network and then apply technical power loss equations. Examples of minimum spanning tree algorithm include Prim's, Sollin’s and Kruskal’s algorithms. Coal transportation cost in terms of dollar per ton per mile will be used with the Euclidian distance equation to calculate linear coal transportation expense. The reason for using the Euclidian distance equation is that it guarantees a short path between two points (Power Plant and Coal Mine) on a smooth surface.

This marks the conclusion of the literature review portion of the thesis project. The next chapter details the proposed methodology, objective functions, formulations, simulation design, and coded variables.

Chapter 3. Methodology

The methodology section is primarily composed of a Java based simulation using dynamic programming strategy. Dynamic programming is a useful mathematical technique for making a sequence of interrelated decisions. It provides a systematic procedure for determining the optimal combination of decisions. The aim of the methodology is constantly improving the objective function of minimizing the electric transmission losses and coal logistics cost under environmental constraints.

The methodology is simulation based due to dynamic range of several variables. Simulation is especially helpful in measuring and predicting the effect of change in value of individual element onto the entire system (Britannica, 2017). For example, the wind speed, the stack height, the exhaust velocity, and temperature of emissions can take a range of different numeric values, resulting in various possible locations for coal power plant's placement. In addition, the shear amount of computations and visual projection makes the manual calculation completely infeasible. For example, a 20 km x 20 km Gaussian plume contour grid with a resolution factor of ½ km contains about 1600 receptor points. To calculate resultant plume concentration for any given plume interaction with a different source of identical grid size, requires 2,560,000 calculations per grid point. Since there are 10,000 grid points on a 100 km x100 km grid with resolution factor of one kilometer, the total amount of computations is enormous and simulation methodology can thus provide the best tool to deal with the problem.

Step Wise Calculation Summary

The program starts with initialization of static locations of multiple stakeholders, i.e. customers, supplier, and resources. Pollution dispersion equations are initialized for current and future power plants, followed by integral placement of the future power plant on all possible locations of a 2D-spatial grid, with the relevant costs of electric transmission and coal transportation calculated at each location. A *key point* is that the algorithm calculates the shortest possible network for electric transmission from power plant to consumers.

At each grid point on the map, the program calculates the costs related to transmission losses and coal distribution, as well as the magnitude of emission's concentrations of the pollutants at ground level. Useful data is saved in a declared holding variable (integer, float, array) and during each step of the program, a minimum cost function is run to either hold or update the holding variables. The ultimate objective of the program is to find an optimal location for placing a new power plant which ensures minimum cost of operation for coal power plant with the least amount of pollutant exposure to the general population.

Input

1. Location coordinates of residential and commercial consumers. Location of coal mines and any existing coal power plants.
2. Power plant's power output (that will determine coal usage) in units of MW.
3. Weather condition (wind speed, direction, solar elevation cloud cover, and temperature).
3. Height of stacks.
4. Transmission line physical properties. Unit cost of kWh charged by plant.

Output

1. Spatial x and y coordinates for coal power plant.
2. Net distance between coal power plant and consumers.

3. Net distance between coal power plant and a mine.
4. Total cost for coal shipment.
5. Total cost of electric power transmission.
6. Visual display of emission concentration contours from coal power plant.

Objective Functions

Minimize: Exposure of Power Plant Emission to Location $x_{i-i'}$, $y_{j-j'}$

Minimize: Coal Shipment Cost + Electric Transmission Cost

Constraints 0 km < Grid x,y < 100 km

$x_{i-i'}$, $y_{j-j'}$ Concentration SO_2, NO_x, $PM_{2.5}$ & PM_{10} < EPA Threshold

Description of Data

Input variables are grid size, grid resolution, emission rate, local air temperature, height of stack, wind direction, wind speed, chemical compounds in exhaust, cost of coal delivery per mile, and values of variables related to different technical losses (Resistive losses and Corona losses). The output variables are the optimal spatial coordinates of a coal power plant, concentration values of chemicals at various distances from the source, the presence of any chemical interaction between two or multiple plants, the total cost of coal delivery per time interval, and total line losses per time value. Program input, processing, and output are all dimensional numbers.

Gaussian Dispersion Model

The Gaussian dispersion model is based upon the Gaussian distribution principle, where the width of the plume is determined by the standard deviation of longitudinal and vertical axes which in turn are dependent on, based on environmental stability, class and travel time. The concentration of particle matter in microgram/cubic meter, at any location x, y from the source can be calculated using the following equation 3 (Macdonald, 2003);

$$C(x,y,z) = \frac{Q}{2\pi U_p \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-H_p)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H_p)^2}{2\sigma_z^2}\right)\right] \quad (3)$$

Where; *Q = emission rate of gas, Up = mean wind speed at the height of the stack, Hp = sum of the actual stack height Hs plus any plume rise ΔH due to initial buoyancy or momentum of release, z = is the vertical distance from ground level, y is the cross-wind distance from stack, σy, σz is the standard deviation of concentration distributions, in the crosswind and vertical direction.*

Euclidian Distance

Distance between two grid points on a grid or map can be calculated using equation 4:

$$Distance = \sqrt{(x_2} - x_1)^2 + (y_2 - y_1)^2 \quad (4)$$

Coal shipment cost to power plant is calculated using equation 5:

$$Cost = Distance\ x\ \frac{Cost}{(Mile-Ton)} \text{ charged by shipment company} \quad (5)$$

In 2009, the cost to ship one ton of coal to one mile was around four cents.

Electric Transmission Cost to Consumers is calculated using equation 6:

$$Losses\ (\$) = \sum_{i=1}^{n} Technical\ losses\ \frac{kW}{km}\ .\ Electric\ load\ .\ Distance\ (km) \quad (6)$$

Where; *n = total number of customers, Technical losses = resistive losses plus corona losses.*

Simulated Annealing

A random-search technique, which exploits a similarity between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system, forms the basis of an optimization technique for combinatorial and other problems (Hillier & Lieberman, 2005).

AC Power Losses

The main costs associated with AC Power Transmission are Resistive and Corona Losses. On average, 6.8% of total power generated gets wasted in these losses (Harting, 2010).

Resistive Losses

$$\%P_{Rloss} = \frac{P(0) - P(z)}{P(0)} = 1 - e^{-zR_l/(Lc)} \qquad (7)$$

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$$

$$R_l = \frac{I_B}{2\pi a \sigma \delta} \quad L = \frac{\mu}{\pi} \ \ln(\frac{d}{a})$$

Corona Losses

$$P = \frac{k_0}{k_d}(f + 25)\sqrt{\frac{a}{d}}[V_0 - g_0 k_i a k_d ln(\frac{d}{a})]^2 \times 10^{-5} \text{ kW/km} \qquad (8)$$

Where; *d = line separation, a = wire radius, f = frequency, IB= bessel correction factor, alpha = attenuation factor, ko = fixed constant, go = disruptive gradient of air, kd = Norm Air Density Factor, ki = wire irregularity factor, Vo = line voltage to neutral, L = inductance/unit length, c = speed of light,* R_l *= resistance per unit length and sigma as wire skin depth.*

Target Population

The program in intended to be used by Industrial Zone Planners, Environmental Agencies, Operations Analysts, Coal Power Plant Owners, and Operations Managers.

Simulation Design

The simulation uses a dynamic programming principle to choose an appropriate location for a power plant which minimizes the electric distribution losses and coal transportation cost while ensuring that the general public's exposure to a given pollutant stays below the National Ambient Air Quality Standards (NIOSH) threshold for that pollutant. The simulation is developed using Processing Language as the primary platform. The Processing Language platform was chosen due to its java-based composition and imbedded visual arts feature. The simulation is primarily composed of the following parts:

1. 2-Dimesnional grid space (100 km x 100 km) with grid resolution of 1 km.
2. 20 customers spread randomly with integer-based x, y spatial values.
3. Three coal mines clustered together within a 30 km vicinity of each other.
4. One existing and one new coal power plant with individual electric generation capacity, coal consumption, stack diameter, and stack height.

5. 2-Dimensional Gaussian plume chemical dispersion contours for a downwind range of 20 km, with a 90-degree West wind and a receptor resolution of 500 m. The horizontal and vertical dispersion coefficient for atmospheric stability classes A, B, C, D, E, and F is used with the Gaussian plume dispersion equation to calculate the dispersion concentration of pollutants in the downwind range at an elevation of ‘0’ m.
6. In the search process for a viable location for a new power plant, if the chemical dispersion contours overlap with a customer location and the chemical concentration is greater than the EPA threshold, it is acknowledged for further processing. The simulation can also successfully detect interaction between two power plant emissions and adjust the overlapping contours of chemical concentration accordingly.
7. Electric demand from each customer is represented in megawatts. Demand is chosen as a random integer value ranging from one megawatt to 100 megawatts.
8. Prims algorithm is applied to find a minimum spanning tree between cities and a new power plant. A minimum spanning tree ensures that the total distance of all nodes, connecting the cities and power plant, is minimized. The reason to use Prim’s algorithm is due to its simplistic nature, availability of code for processing language software, running time complexity of $O(n^2)$, ability to start a minimum spanning tree from a given vertex and suitability to calculate the non-linear electrical losses by back tracking on the resultant minimum spanning tree. The Kruskal algorithm does not guarantee a start from a given vertex, and the coding

complexity of Sollin's algorithm made it non-preferential for usage (Skiena,2008; Shiffman, 2016; Erickson, 2015).

9. Prim's algorithm is also applied to find a minimum spanning tree between the power plant and the coal mines.
10. Regressive load transfer. A non-linear concept is applied to calculate the cost of electric distribution losses from power plant to various customers located on the tree, since the net electric load from the source (Power Plant) reduces proportionally as each customer's demand on the network is satisfied. The load bearing cost reduces proportionally as deliveries are made. The net cost of electrical losses is calculated by back tracking on the network produced by Prim's algorithm; start with the leaf nodes (Customers) and making way to source node (Power Plant).

    The concept of 'Regressive load transfer' to calculate the cost of electrical losses is more 'optimal' than ones found using the 'average' approach. The average cost can be calculated simply by multiplying given line losses value for corresponding net electric load, by the total network distance. However, the 'average' approach does not represent realistic application and the line losses cost calculated is significantly higher, compared to 'Regressive load transfer' concept.
11. The simulations tests all 10,000-location points for a candidate solution.

Simulation Step-Wise Process

The simulation is initiated by declaring a variety of global variables. The key global variables declared at the start of simulation are as follows.

Void Generic

1.	'PVector' x, y	Two power plants with x, y location using PVector class.
2.	Int 'Count' and 'Step'	These variables are key drivers for testing all x and y values on the grid.
3.	Float 'dist_PP'	These variables are used to calculate Euclidean distance between two power plants.
4.	FloatList 'Uncustx' FloatList 'Uncusty' FloatList 'Custx' FloatList 'Custy'	Declared for potential customers. 'Uncust' and 'Cust' FloatList are fundamental in running Prim's algorithm
5.	FloatList 'Leafx' FloatList 'Leafy' FloatList 'Leafw' FloatList 'Leafld'	Declared to process leaf nodes in a spanning tree. 'Leafx' and 'Leafy' donate x, y location of the customer, 'Leafw' donate the electric load on the customer while 'Leafld' donate the net distance between leaf node and parent node.
6.	Float 'min_Elec_Cost'	Declared for storing the combined, minimum cost of electric transmission losses and coal delivery cost.

Void Coal

1.	FloatList 'Uncoalx' FloatList 'Uncoaly' FloatList 'Coalx' FloatList Coaly'	Declared for potential coal mines. 'Uncoal' and 'Coal' FloatList are fundamental in running Prim's algorithm between coal mines and a new power plant.
2.	Float 'deliv_cpm'	Delivery cost per mile per ton.

3. Int 'coal_trian-load — Train load carrying capacity.

Void Electric Losses

1. Float 'Line_Voltage' — Line voltage of transmission lines.
2. Float 'Price_KWH' — Price per kilo-watt hour.

Void Grid

1. Int 'grid_alpha' — Size of search space. In this simulation it is 100 x 100 km grid.

Void Plume Modeling

1. Int 'Guass_Resolution' — Number of receptors within 1 km grid.
2. Int 'Down_Wind_Range' — Gaussian plume dispersion downwind range.
3. Float 'chemobs_start' — Receptor point closest to chimney.
4. Float 'sdy' Float 'sdz' — Represents horizontal and vertical dispersion rates used in the Gaussian plume dispersion equation.
5. Float Array
   'C1 [Down_Wind_Range][Down_Wind_Range]'
   'C2 [Down_Wind_Range][Down_Wind_Range]'
   Declared to store pollutant concentration at ground level at different receptor points.

6. Float 'Chem_min' Float 'Chem_max' — Used to store maximum and minimum calculated chemical concentration values.
7. Boolean 'stayaway' — Used to declare a 'true' or 'false' statement per that plume is interacting with a customer location and that the plume concentration is greater than EPA threshold for that given pollutant.

8.	Float Qn[4]	Emission rate of pollutant from chimney.
9.	Float Vsn[3]	Exit velocity of gas from stack.
10.	Int dsn[3]	Exit diameter of stack.
11.	Float usn[3]	Wind speed at stack height.
12.	Int Qhn[3]	Heat emission rate.
13.	Int Stack_Hn[3]	Stack structural height
14.	String Classif "[5]"	Briggs atmospheric classification.

Setup

Setup process is used to define the initial environment. It is also used to populate various large scale dimensional arrays using ‘for’ loop. Setup function is only run once during course of a simulation. Key parts of a setup process are as follow;

1. Generate a ‘random’ x and y value for old power plant between ranging between 0 and 80.
2. Use a ‘for’ loop to generate 25 random values, ranging between 1 and 100 for Float ‘POWER_CONSUMP’ array. Those values represent the megawatt demand for 25 individual customers.
3. Calculate the Resistive Losses per the net difference between power delivered to each customer versus the total power generated.
4. Calculate the value of Corona Losses in *kilowatt/ line/ kilometer* of transmission line.
5. Calculate the final plume rise.

[4] ‘n’ represents a value of 1 and 2. ‘1’ relates to characteristics related to old power plant, while ‘2’ relates to characteristics related to new power plant.
[5] Classification A, B, C, D, E, F

6. Calculate the horizontal and vertical standard deviations of dispersions per given downrange distance from emission source.
7. Calculate pollutant concentrations at numerous grid points using Gaussian plume dispersion equation and store resultant values in a dedicated array for each power plant. The maximum and minimum pollutant concentration values can then be extracted from the array and can be stored separately for visual contour referencing.

Draw

The 'Draw' function continuously executes a set of commands until the program is manually terminated or nested conditions are met. In this simulation the draw function is running Prim's algorithm on 10,000 potential sites and checking following Boolean statement on each site: "Is the pollutant concentration greater than the EPA threshold for a set of customers located within the sphere of Gaussian plume dispersion plane?" (The plane size is 20 km x 20 km)

Key parts of a draw process are as follow: (This process is repeated 10,000 times)

1. The 'background' environment is initialized.
2. FloatList 'Uncustx', 'Uncusty', 'Uncoalx' and 'Uncoaly' with integer values of x and y are populated. The 'x' and 'y' values correspond to spatial coordinates of a given 'customer' or 'coal mine' on the grid space.
3. The visual output of grid is produced.
4. The net Euclidean distance between old and new power plant is calculated.
5. The chemical contour trail of emissions are visually produced.
6. A detection protocol is run to check interaction, between emissions of two power plants.

7. Another detection protocol is run to check any plume emission interaction with a set of customers located in the sphere of Gaussian plume dispersion plane.
8. The Prim's algorithm is run to find the minimum spanning tree to connect all customers.
9. To calculate the cost of combined electric losses the Regressive load transfer concept is applied which starts from a set of leaf and a set of parent nodes and through successive pruning; concluded at a single source node (Coal Power Plant).
10. The Prim's algorithm is then run to find the minimum spanning tree to connect all coal mines to the coal power plant.
11. The cost of coal delivery is calculated on the minimum spanning tree.
12. The cost of electric distribution and coal delivery are summed together. If the cost of electric distribution and coal delivery is less than the previously calculated value and the emission exposure for a set of customers within the Gaussian plume sphere is less than the EPA threshold, then the stored position value for the new coal power plant is updated.
13. The new coal power plant is moved by a magnitude of '1' in x-direction.
14. If value of new power plant 'x' location is 100, then x is set to 0 and y is updated to a value of 1.
15. If value of x is 100 and y is 100 then the search is concluded! The corresponding x and y value of 'min_Elec_Cost' is declared as a good candidate location for placement of a new coal power plant. *Else:* the processes is again repeated by starting at step 1.

This marks the conclusion of the methodology portion of the thesis project. The next chapter deals with data analysis and results. Chapter focuses on validation of Prims algorithm used to create minimum spanning tree, validation of Gaussian plume dispersion models under atmospheric condition A-F, coal logistics and transmission line resistive and corona losses.

Chapter 4. Data Analysis and Results

Prim's Algorithm

The validation of Prim's algorithm is a multi-step process. Prim's algorithm illustration from Network Flows Theory, Algorithms, and Application (Ahuja, Magnanti, & Orlin, 1993) as shown in Figure 9 is run on R-software[6]. Upon successful match between reference and R-output; a separate network of five individual customers is created both in the simulation algorithm as well as in R-software. A graphical output of the simulation program is compared against R-software output as shown in Figure 10. A successful match indicates that Prim's algorithm has been accurately programmed to provide a minimum spanning tree.

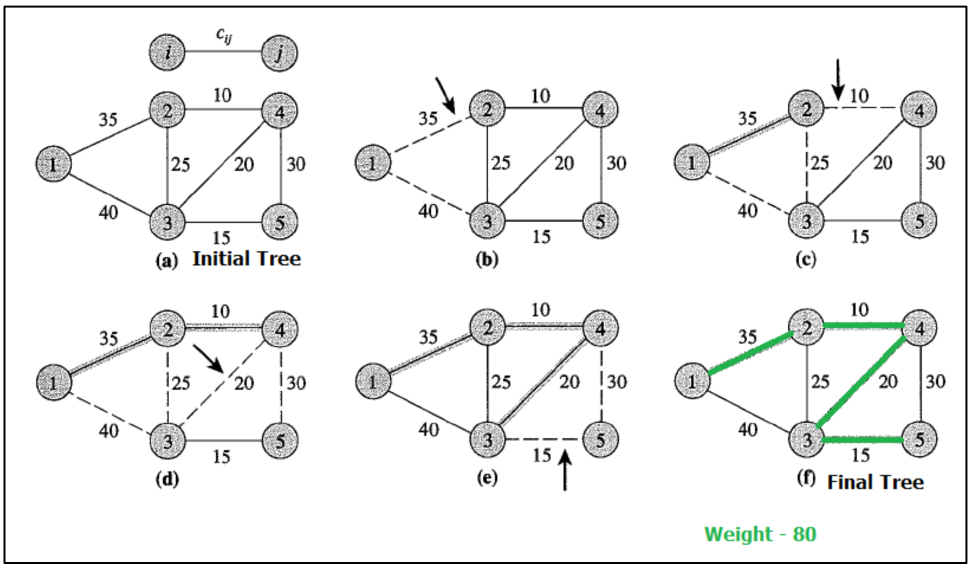


Figure 9. Prims algorithm illustration *(Ahuja, Magnanti, & Orlin, 1993)*

[6] 'Optrees' Package Command: getMinimumSpanningTree(nodes, arcs, algorithm = "Prim").

R-Validation

```
> # Graph
> require(optrees)
> nodes <- 1:5
> arcs <- matrix(c(1,2,35, 1,3,40, 2,3,25, 2,4,10, 3,4,20, 3,5,15, 4,5,30),
+ ncol = 3, byrow = TRUE)
> # Minimum cost spanning tree with several algorithms
> getMinimumSpanningTree(nodes, arcs, algorithm = "Prim")

 Minimum Cost Spanning Tree
 Algorithm: Prim
 Stages:  4 | Time:  0
 ------------------------------
      ept1      ept2     weight
         1         2         35
         2         4         10
         4         3         20
         3         5         15
 ------------------------------
                     Total = 80
```

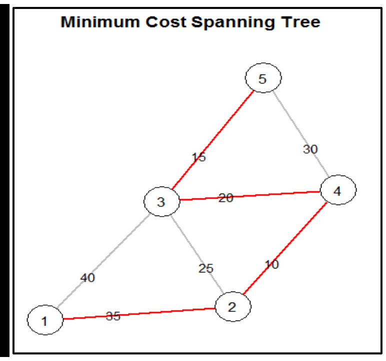


Figure 10. Prims algorithm numerical and visual output using R software

Prim's Application in Simulation

Figure 11 represents visual demonstration of total number of edges to connect six customers with each other. A complete graph is a graph, where each pair of graph vertex is connected by an edge. The total number of edges for a graph containing (6) vertices equals (30) and is obtained by using formula $\frac{n(n-1)}{2}$ where n equal total number of vertices (Weisstein, 2018).

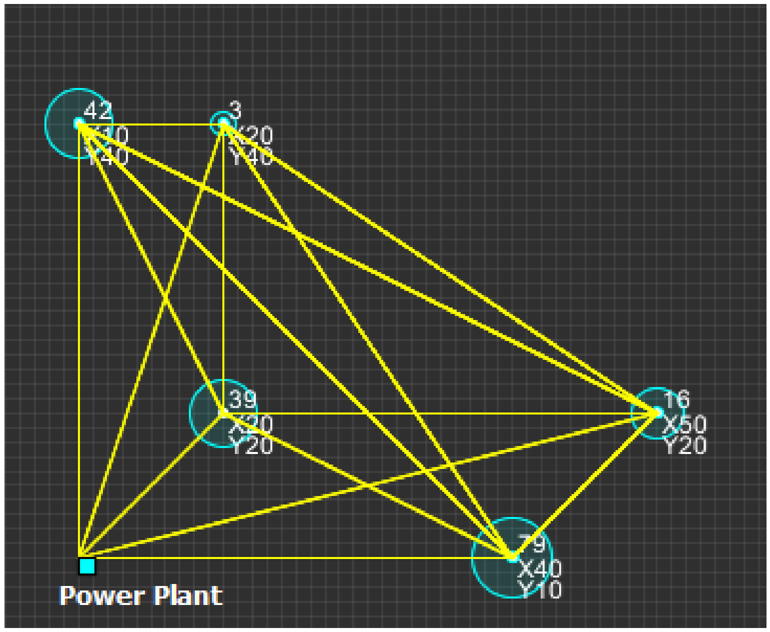


Figure 11. A complete graph representing all possible paths between cities and a power plant.

A minimum spanning tree of a graph is a subset of edges whose sum of edge weights is the lowest. A minimum spanning tree can be one solution when electric junctions need to be joined with minimum amounts of wire. Figure 12 demonstrates how an application of Prim's algorithm in Figure 11 produced a minimum spanning tree of a total distance of 80.64 km. The Prim's algorithm starts from the power plant and then iteratively connects cities for power based upon the lowest edge weights and minimum transmission distance (Skiena, 2008).

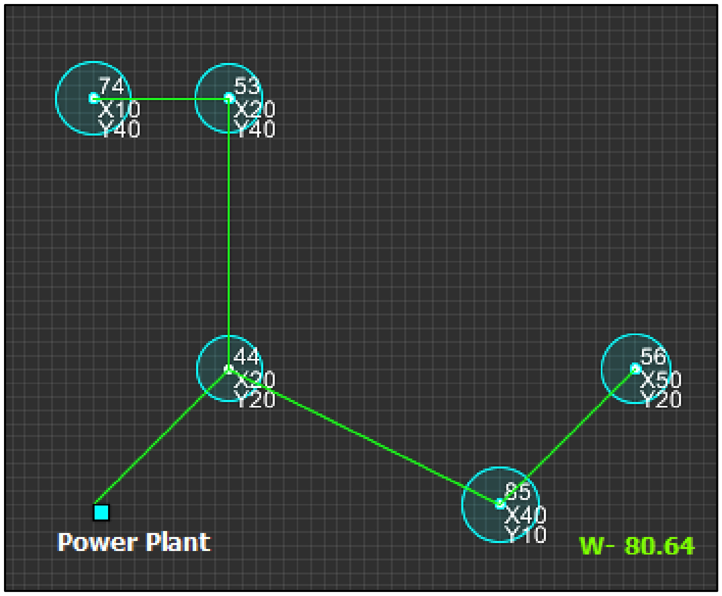


Figure 12. Visual output of Prim's minimum spanning tree with total path distance of 80.64 km

R-Validation

The Prim's algorithm minimum spanning tree output from the developed simulation is validated using R-Software-Optress Package. As shown in Figure 13, the total weight of all paths is '80.64', which is equal to the total weight of all edges as depicted in Figure 12. This concludes that Prim's algorithm coded in the simulation is working properly. The visual layout of the R-output, as shown in Figure 14, is different than that on Figure 12, since the edges are not scaled, and positioning of vertices is random.

```
> # Graph
> require(optrees)
> nodes <- 1:6
> arcs <- matrix(c(
+ 1 , 2 , 14.142136,
+ 1 , 3 , 30.0 ,
+ 1 , 4 , 41.23,
+ 1 , 5 , 30.0,
+ 1 , 6 , 31.623,
+ 2 , 3 , 22.36,
+ 2 , 4 , 30,
+ 2 , 5 , 22.36,
+ 2 , 6 , 20,
+ 3 , 4 , 14.142136,
+ 3 , 5 , 42.43,
+ 3 , 6 , 36.05,
+ 4 , 5 , 44.72,
+ 4 , 6 , 36.05,
+ 5 , 6 , 10),ncol = 3, byrow = TRUE)
> getMinimumSpanningTree(nodes, arcs, algorithm = "Prim")

 Minimum Cost Spanning Tree
 Algorithm: Prim
 Stages:  5 | Time:  0
 ------------------------------
      ept1     ept2     weight
         1        2   14.14214
         2        6   20.00000
         6        5   10.00000
         2        3   22.36000
         3        4   14.14214
 ------------------------------
                  Total = 80.64427
```

Figure 13. Prim’s algorithm numerical output using R software-Optrees Package.

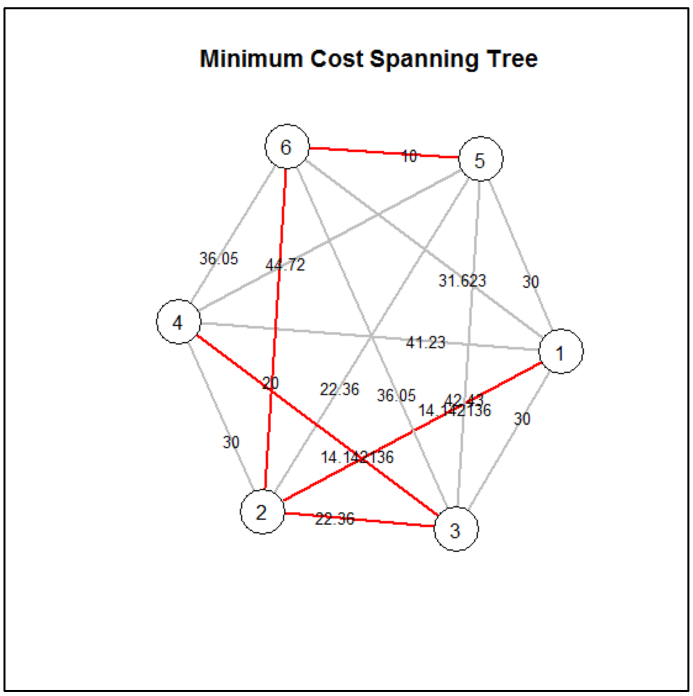


Figure 14. R-software-Optrees Package, Prim’s algorithm visual output.

Regressive Load Transfer

In the validation process, total electric demand from five customers is set equal to 213 MW. Electric power gets generated at the power plant and is channeled to cities using a single 765 kV transmission line. The term 'regressive load transfer' represents the following steps:

1. Leaf cities on the minimum spanning tree demand electric power from their immediate parent cities. In the above graph, node **(x_{50}, y_{20})** has a demand of 73 MW and node **(x_{10}, y_{40})** has a demand of 49 MW. Node **(x_{50}, y_{20})** demands 73 MW from the immediate parent node of **(x_{40}, y_{10})**, while **(x_{10}, y_{40})** demands 60 MW from the immediate parent node of **(x_{20}, y_{40})**.
2. Distance is calculated between **(x_{50}, y_{20})** and **(x_{40}, y_{10})** which equals 14.142 km, while distance between **(x_{10}, y_{40})** and **(x_{20}, y_{40})** equals 10.00 km. Resistive losses are calculated using equation 7, which incorporates the inductive and resistive properties of transmission line and total distance. Net Corona Losses are calculated based upon transmission line voltage, frequency, and net distance between two cities using equation 8 (Harting, 2010).
3. Node **(x_{50}, y_{20})** and **(x_{10}, y_{40})** are then deleted from the minimum spanning tree. Now node **(x_{40}, y_{10})** and **(x_{20}, y_{40})** are leaf nodes. The **(x_{40}, y_{10})** node has a total demand of 142 MW (73 MW from (x_{50}, y_{20}) and 68 MW from itself). The same principle applied to the **(x_{20}, y_{40})** node.
4. Step 1, 2 and 3 are iterated until the power plant is the only vertex left on the minimum spanning tree. Refer to Figure 15 for visual conceptualization.

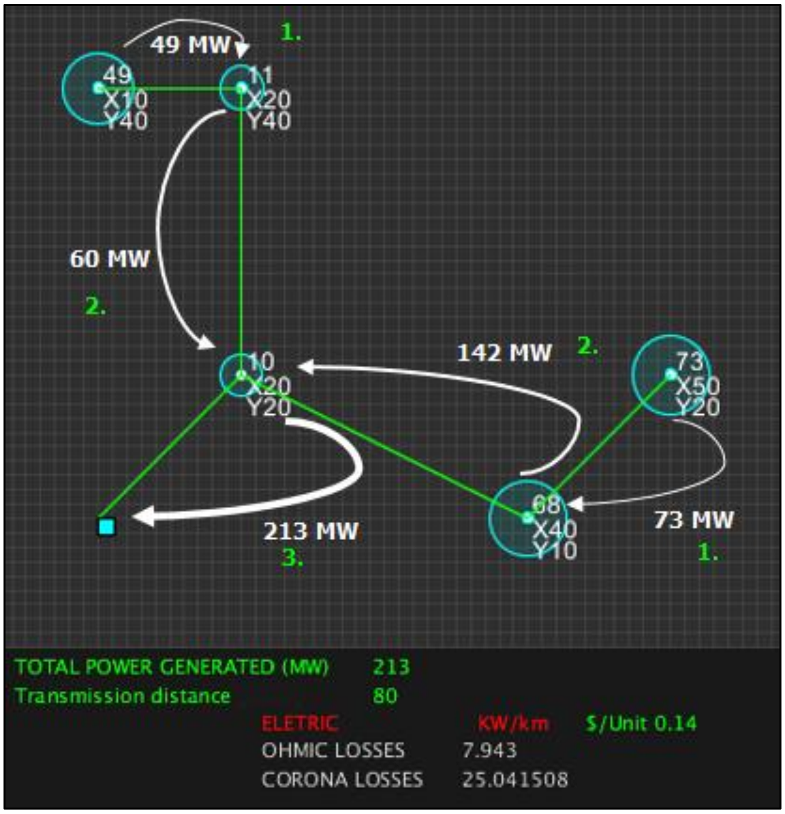


Figure 15. Visual conceptualization of regressive load transfer

The iterative process of regressive load transfer is used to calculate total cost of Resistive and Corona Losses as shown in Figure 16. Total power demand by five cities equals 213,000 kWh, which equates to $ 29,820 (at the rate of 14 cents/kWh). Net resistive and Corona Losses equate the cost of $ 329.41 to transmit 213 MW power over a total transmission distance of 80.64 KM. In terms of dollar value, the transmission losses are only 1.105% of the total value of electric power generated.

```
Iter # 1
n Leaf-x    FloatList size=2 [ 10.0, 50.0 ]
n Leaf-y    FloatList size=2 [ 40.0, 20.0 ]
n Leaf-w    FloatList size=2 [ 49.2, 73.8 ] ________ Demand
n Leaf-Load FloatList size=2 [ 10.0, 14.142136 ] _____ Distance
n LEAF R $  FloatList size=2 [ 2.5651588, 5.4409037 ] Resistive Losses $ Cost
n LEAF C $  FloatList size=2 [ 35.05811, 49.57966 ] __ Corona Losses $ Cost
n TOTAL $   FloatList size=1 [ 92.64383 ] __________ Cumulative Net $ Cost
Iter # 2
n Leaf-x    FloatList size=2 [ 20.0, 40.0 ]
n Leaf-y    FloatList size=2 [ 40.0, 10.0 ]
n Leaf-w    FloatList size=2 [ 61.0, 142.0 ]
n Leaf-Load FloatList size=2 [ 20.0, 22.36068 ]
n LEAF R $  FloatList size=2 [ 6.3597417, 16.551247 ]
n LEAF C $  FloatList size=2 [ 70.11622, 78.39232 ]
n TOTAL $   FloatList size=1 [ 264.06335 ]
Iter # 3
n Leaf-x    FloatList size=1 [ 20.0 ]
n Leaf-y    FloatList size=1 [ 20.0 ]
n Leaf-w    FloatList size=1 [ 213.8 ]
n Leaf-Load FloatList size=1 [ 14.142136 ]
n LEAF R $  FloatList size=1 [ 15.762402 ]
n LEAF C $  FloatList size=1 [ 49.57966 ]
n TOTAL $   FloatList size=1 [ 329.4054 ]
END
```

Figure 16. Iterative regressive load transfer strategy

Plume Stack Height

Briggs plume rise equations are used to calculate the effective height of a buoyancy dominated plume for input parameters as shown in Table 1. Since the exit velocity of the plume (18.31m/s) is greater than (1.5 x Wind Velocity) at stack height, no downwash is expected. Distance to the final rise is the ground level distance from stack structure in the mean wind direction, where the plume height peaks out. Simulation output indicates that for a stack height of 30.48 m, with an emission rate of 28.85 g/s, exit velocity of 18.31 m/s, and exit temperature of the plume of 372.04 K, the effective height of the plume is 419.26 m at a range of 1213.78 m from the stack structure in the direction of the wind (EPA, 1995). Figure 17 shows a visual representation of the buoyancy dominated plume evolution up to a range of 1500 m. The final effective height (marked by a red arrow) has been validated using the Screen 3 EPA Model. See Screen 3-Classification Table 5.

Table 1. Buoyancy dominated plume rise

```
***THESIS PROJECT OUTPUT***
Input:
Medium              Gas
Emission      (g/s)28.85
Exit Vel      (m/s)18.31
Exit Temp     (K  )372.04
U10           (m/s)3.0
U10 Temp      (K  )281.01
Stack Height  (m  )30.48

Modified Height hs'  30.48 vs > 1.5u  (Eq 1-7)
Buoyancy Flux  332.26514              (Eq 1-8)
Momentum Flux  1915.0239              (Eq 1-9)
Crossover Temp Diff  8.417878         (Eq 1-10/11)
Dist to final rise   1213.7825        (Eq 1-12/13)
Effective Height     419.26706        (Eq 1-14/15)
```

(x)	Effective Height (m)
3.125	37.8
6.25	42.0
12.5	48.8
25	59.6
50	76.6
100	103.7
200	146.7
300	182.7
400	214.9
500	244.4
600	272.0
700	298.2
800	323.1
900	346.9
1000	369.9
1100	392.2
1200	413.8
1300	419.3
1400	419.3

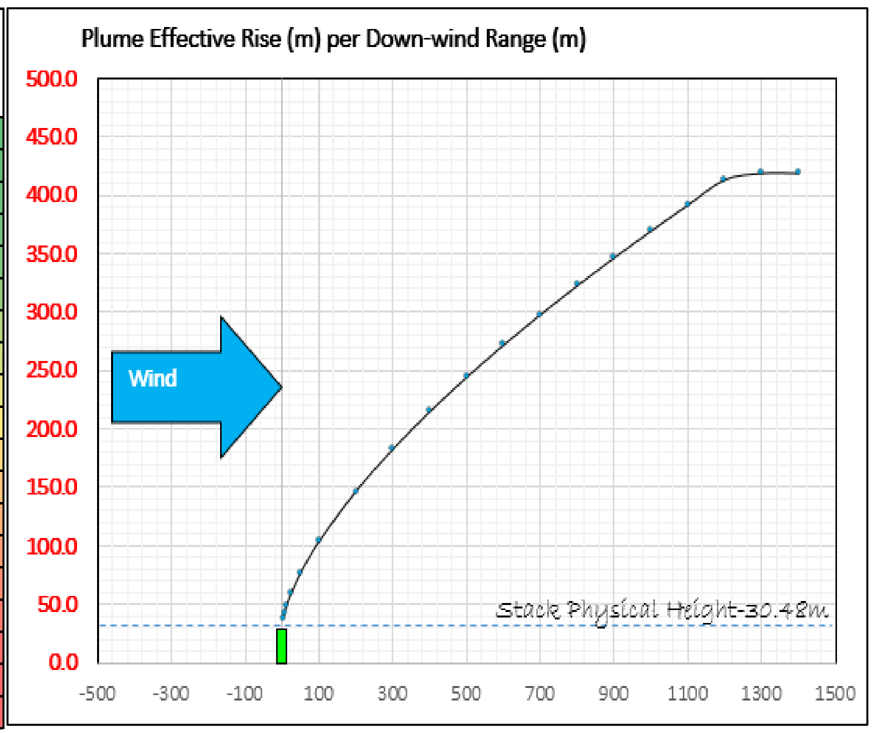


Figure 17. Graphical output representing (Buoyancy Dominated) plume height evolution

Briggs plume rise equations were also used to calculate the effective height of a momentum dominated plume for input parameters as shown in Table 2. Since the exit velocity of the plume (18.31m/s) is greater than 1.5 x Wind Velocity at stack height or (4.86 m/s), no downwash is expected. Simulation output indicates that for a stack height of 30.48 m, with an emission rate of 28.85g/s, an exit velocity of 18.31 m/s, and an exit temperature of the plume of 285 K, the effective height of the plume is 123.62 m at a range of 308.73 m from the stack structure in the direction of the wind (EPA, 1995). Figure 18 shows a visual representation of buoyancy dominated plume evolution up to a range of 1500 m. The final effective height (marked by red arrow) has been validated using Screen 3 EPA Model (Table 3).

Table 2 Momentum Dominated Plume Rise

```
***THESIS PROJECT OUTPUT***
Input:
Medium                Gas
Emission      (g/s)28.85
Exit Vel      (m/s)18.31
Exit Temp     (K  )285.0
U10           (m/s)3.0
U10 Temp      (K  )281.01
Stack Height  (m  )30.48

Modified Height hs'  30.48 vs > 1.5u (Eq 1-7)
Buoyancy Flux  19.011522             (Eq 1-8)
Momentum Flux  2499.879              (Eq 1-9)
Crossover Temp Diff  7.160273        (Eq 1-10/11/18)
Dist to final rise   308.732         (Eq 1-24)
Effective Height     123.62723       (Eq 1-16/23)
```

(x)	Effective Height (m)
0.5	41.58
1	44.47
3.125	50.9
6.25	56.3
12.5	62.9
25	71.4
50	82.0
100	95.4
200	112.3
300	124.1
350	123.6
400	123.6
500	123.6

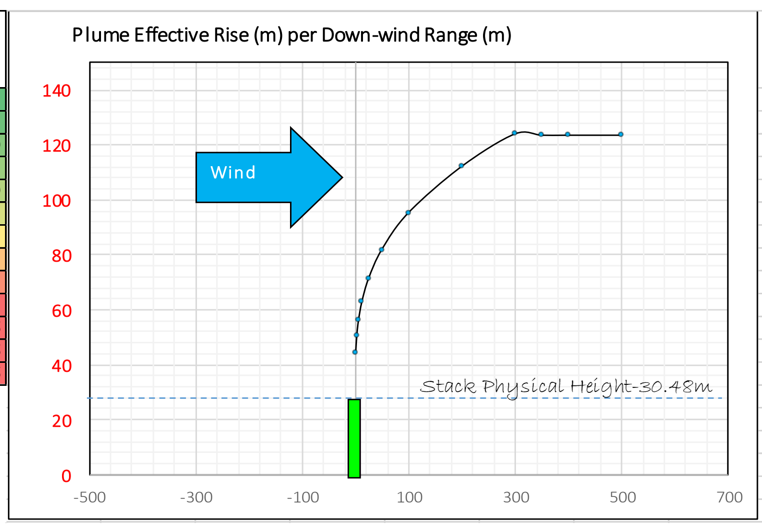


Figure 18. Graphical output representing (Momentum Dominated) plume height evolution

Table 3. Screen 3 model output for Rural/ Atmospheric Classification 'A' per input parameters as shown in Table 2

```
Class A-Rural
**********************************
*** SCREEN AUTOMATED DISTANCES ***
**********************************

*** TERRAIN HEIGHT OF    0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***

  DIST      CONC              U10M   USTK  MIX HT   PLUME   SIGMA    SIGMA
   (M)    (UG/M**3)    STAB  (M/S)  (M/S)    (M)    HT (M)   Y (M)    Z (M)   DWASH
-------  ----------    ----  -----  -----  ------   ------  ------   ------   -----
     1.    0.000         1     3.0    3.2   960.0   123.63    4.02     4.00     NO
   100.   0.2572E-02     1     3.0    3.2   960.0   123.63   32.64    23.21     NO
```

Gaussian Plume Dispersion Validation

Table 4. Input data used for validation of Gaussian plume dispersion model for atmospheric conditions (A-F).

Code Line	Power Plant Emission	
	Compound	**SO2**
71	Emission Per Second (Grams)	28.85
	Atmospheric Condition	**A,B,C,D,E,F**
	Stack Flow (Cubic Meter/Hour)	1,566,341.91
	Stack Flow (Cubic Meter/Sec)	435.09
	Stack Diameter *(Estimated) meter*	5.50
72	Gas Exit Velocity (m/s)	18.31
80	Stack Gas Exit Temperature (K)	372.04
75	Stack Height	30.48
57	10m-Wind (Min) m/s	3.00
57	10m-Wind (Max) m/s	4.52
60	10m-Ambient Temperature (K)	281.01
	Thermal (MWh)	1,115.00
	Electric (MWh)	401.00
	Efficency	36% [7]

[7] The data has been provided by courtesy of DaLyn Hugo, Environmental Coordinator at Basin Electric Power Cooperative. Dry Fork Station 12460 N Highway 69 | Gillette, WY 82716. Dry Fork Station is coal-based power plant with generational capacity of 400 MW.

Gaussian Plume Dispersion - Class A

Input parameters in the simulation code were as follows: a stack height of 30.48 m, a stack diameter of 5.5 m, an emission rate of 28.85 g/s, an exhaust gas exit velocity of 18.31 m/s, an exhaust gas temperature of 372.04 K, wind speed of 3 m/s at the 10 m elevation, ambient temperature of 281.01 K, and a flat plane.

Output results (Table 5) indicate pollutant concentration in the downwind range from the stack, stack effective height, range to effective height, a true condition on 'Buoyancy', vertical and horizontal dispersion standard deviations as a function of downrange distance in wind direction. See Appendix 1 for horizontal dispersion standard deviation and Appendix 2 for vertical dispersion standard deviation as a function of downwind distance from source. Each atmospheric condition (A-E) has its individual dispersion rates for emitted pollutant distribution. Classification A is considered an unstable atmosphere.

Per the given input parameters, Figure 19 demonstrates the visual representation of pollutant concentration. The maximum chemical concentration of 21.53 ug/m^3 is calculated at a range of one kilometer from the stack in the downwind direction. Screen3 provides a maximum concentration of 19.26 ug/m^3 at a range of 0.874 km while METI-LIS provides a maximum concentration of 16.46 ug/m^3 SO_2 at a range of 0.606 km.

The output table has been validated using a Screen3 EPA Model (Table 6).

Table 5. Gaussian plume dispersion table for atmospheric condition A

```
***THESIS PROJECT OUTPUT***
Input:
Medium              Gas
Emission      (g/s)28.85
Exit Vel      (m/s)18.31
Exit Temp     (K  )372.04
U10           (m/s)3.0
U10 Temp      (K  )281.01
Stack Height  (m  )30.48

Output;
Receptor Height:0m   Geography: Rural   Atm-Classification: A   Wind Velocity-Stk(h): 3.24
```

x	Conc ug/m3	Stack-Eff (H)	Stack_Eff (x)	Buoyancy	Momentuem	SD(y)	SD(z)
0.5	15.65	419.27	1213.78	true	false	113.04	104.65
1	21.53	419.27	1213.78	true	false	208.71	453.85
2	3.67	419.27	1213.78	true	false	383.62	1968.21
3	1.11	419.27	1213.78	true	false	546.38	4642.88
4	0.80	419.27	1213.78	true	false	701.34	5000.00
5	0.66	419.27	1213.78	true	false	850.57	5000.00
6	0.57	419.27	1213.78	true	false	995.25	5000.00
7	0.50	419.27	1213.78	true	false	1136.17	5000.00
8	0.44	419.27	1213.78	true	false	1273.88	5000.00
9	0.40	419.27	1213.78	true	false	1408.81	5000.00
10	0.37	419.27	1213.78	true	false	1541.25	5000.00
11	0.34	419.27	1213.78	true	false	1671.48	5000.00
12	0.31	419.27	1213.78	true	false	1799.70	5000.00
13	0.29	419.27	1213.78	true	false	1926.08	5000.00
14	0.28	419.27	1213.78	true	false	2050.76	5000.00
15	0.26	419.27	1213.78	true	false	2173.87	5000.00
16	0.25	419.27	1213.78	true	false	2295.52	5000.00
17	0.23	419.27	1213.78	true	false	2415.80	5000.00
18	0.22	419.27	1213.78	true	false	2534.79	5000.00
19	0.21	419.27	1213.78	true	false	2652.56	5000.00
20	0.20	419.27	1213.78	true	false	2769.19	5000.00

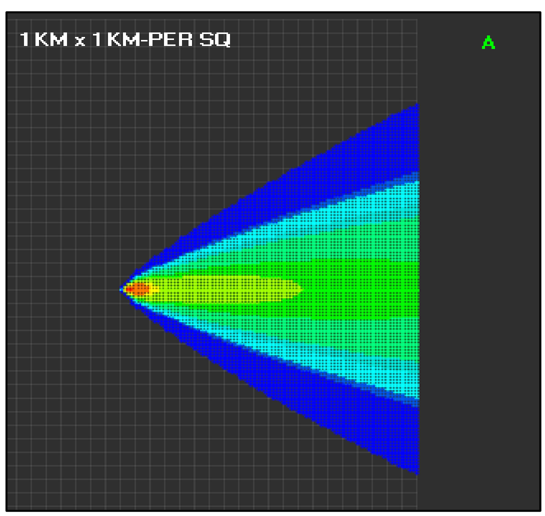


Figure 19. Visual representation of pollutant concentration for atmospheric condition A up to downwind range of 20 km.

Screen3

Screen3 is the Environmental Protection Agency (EPA) single source Gaussian plume model that provides maximum ground level pollutant concentrations for flare, point, and volume sources. The model can provide pollutant concentration in the cavity zone as well as the concentration of pollutant due to inversion break up. Screening models are applied to check suitability of the given scenario for further sophisticated modelling (EPA, 2016).

METI-LIS

METI-LIS is a Gaussian dispersion model developed by the Japanese Ministry of Economy, Trade, and Industry (METI) and Japanese Research Center for Chemical Risk Management (CRM) based upon EPA ISC model. METI-LIS not only provides a simple solution to plume and puff models, but it also incorporates the effect of downdraft around buildings. METI-LIS does not use Briggs equations for effective plume height but instead uses the CONCAWE equation. The model can also calculate deposition concentration of particle matter (METI, 2005).

Screen3 Validation (Class - A)

Table 6. Screen3 model output for atmospheric classification ‘A’.

➔ Note: Input parameters are the same as in Table 5.

```
**********************************
*** SCREEN AUTOMATED DISTANCES ***
**********************************

*** TERRAIN HEIGHT OF    0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***
```

DIST (M)	CONC (UG/M**3)	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
1.	0.000	1	3.0	3.2	960.0	419.25	3.68	3.66	NO
100.	0.000	1	3.0	3.2	960.0	419.25	34.11	25.24	NO
200.	0.000	1	3.0	3.2	960.0	419.25	60.10	44.42	NO
300.	0.3568E-06	1	3.0	3.2	960.0	419.25	84.05	64.53	NO
400.	0.4240E-02	1	3.0	3.2	960.0	419.25	106.79	88.73	NO
500.	0.4654	1	3.0	3.2	960.0	419.25	128.68	121.38	NO
600.	5.131	1	3.0	3.2	960.0	419.25	149.93	168.88	NO
700.	13.25	1	3.0	3.2	960.0	419.25	170.65	226.78	NO
800.	18.33	1	3.0	3.2	960.0	419.25	190.93	295.24	NO
900.	19.17	1	3.0	3.2	960.0	419.25	210.83	374.36	NO
1000.	17.75	1	3.0	3.2	960.0	419.25	230.41	464.23	NO
1100.	15.83	1	3.0	3.2	960.0	419.25	249.69	564.95	NO
1200.	14.22	1	3.0	3.2	960.0	419.25	268.71	676.63	NO
1300.	13.12	1	3.0	3.2	960.0	419.25	285.43	798.60	NO
1400.	12.29	1	3.0	3.2	960.0	419.25	301.81	931.78	NO
1500.	11.63	1	3.0	3.2	960.0	419.25	318.17	1076.35	NO
1600.	11.05	1	3.0	3.2	960.0	419.25	334.50	1232.32	NO
1700.	10.54	1	3.0	3.2	960.0	419.25	350.79	1399.76	NO
1800.	10.07	1	3.0	3.2	960.0	419.25	367.04	1578.70	NO
1900.	9.645	1	3.0	3.2	960.0	419.25	383.23	1769.21	NO
2000.	9.256	1	3.0	3.2	960.0	419.25	399.37	1971.35	NO
2100.	8.897	1	3.0	3.2	960.0	419.25	415.46	2185.16	NO
2200.	8.567	1	3.0	3.2	960.0	419.25	431.48	2410.71	NO
2300.	8.261	1	3.0	3.2	960.0	419.25	447.45	2648.06	NO
2400.	7.978	1	3.0	3.2	960.0	419.25	463.36	2897.26	NO
2500.	7.714	1	3.0	3.2	960.0	419.25	479.20	3158.35	NO
2600.	7.468	1	3.0	3.2	960.0	419.25	494.99	3431.41	NO
2700.	7.238	1	3.0	3.2	960.0	419.25	510.72	3716.47	NO
2800.	7.022	1	3.0	3.2	960.0	419.25	526.38	4013.59	NO
2900.	6.820	1	3.0	3.2	960.0	419.25	541.99	4322.82	NO
3000.	6.630	1	3.0	3.2	960.0	419.25	557.54	4644.21	NO
3500.	5.826	1	3.0	3.2	960.0	419.25	634.46	5000.00	NO
4000.	5.206	1	3.0	3.2	960.0	419.25	710.07	5000.00	NO
4500.	4.712	1	3.0	3.2	960.0	419.25	784.47	5000.00	NO
5000.	4.309	1	3.0	3.2	960.0	419.25	857.77	5000.00	NO
5500.	3.974	1	3.0	3.2	960.0	419.25	930.06	5000.00	NO
6000.	3.691	1	3.0	3.2	960.0	419.25	1001.41	5000.00	NO
6500.	3.449	1	3.0	3.2	960.0	419.25	1071.89	5000.00	NO
7000.	3.238	1	3.0	3.2	960.0	419.25	1141.56	5000.00	NO
7500.	3.054	1	3.0	3.2	960.0	419.25	1210.48	5000.00	NO
8000.	2.891	1	3.0	3.2	960.0	419.25	1278.69	5000.00	NO
8500.	2.746	1	3.0	3.2	960.0	419.25	1346.24	5000.00	NO
9000.	2.616	1	3.0	3.2	960.0	419.25	1413.15	5000.00	NO
9500.	2.498	1	3.0	3.2	960.0	419.25	1479.47	5000.00	NO
10000.	2.392	1	3.0	3.2	960.0	419.25	1545.22	5000.00	NO
15000.	1.698	1	3.0	3.2	960.0	419.25	2176.67	5000.00	NO
20000.	1.334	1	3.0	3.2	960.0	419.25	2771.36	5000.00	NO

ITERATING TO FIND MAXIMUM CONCENTRATION . . .

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 1. M:

DIST (M)	CONC (UG/M**3)	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
874.	19.26	1	3.0	3.2	960.0	419.25	205.89	353.57	NO

METI-LIS Validation (Class - A)

METI-LIS provides maximum concentration of 16.46 ug/m^3 at range of 0.606 km.

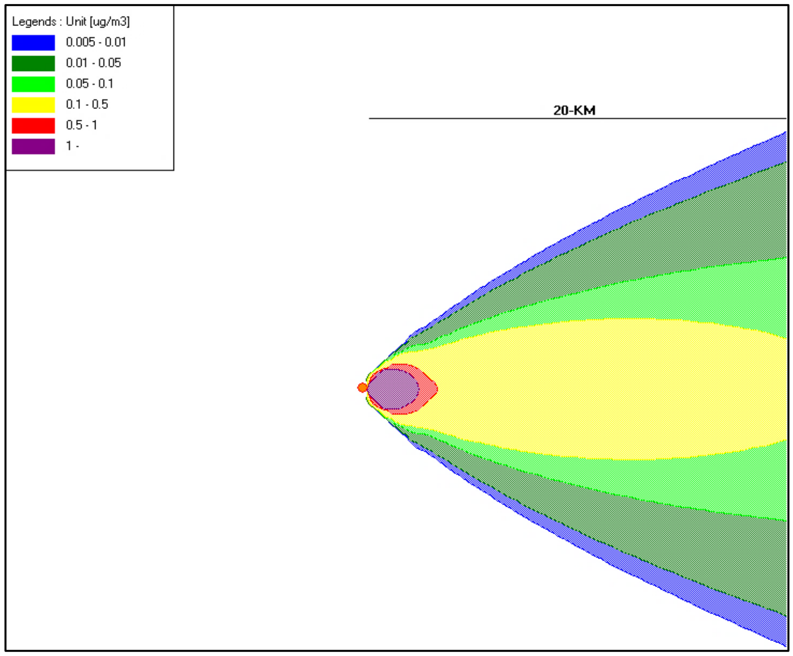


Figure 20. METI-LIS Visual representation of pollutant concentration for condition A.

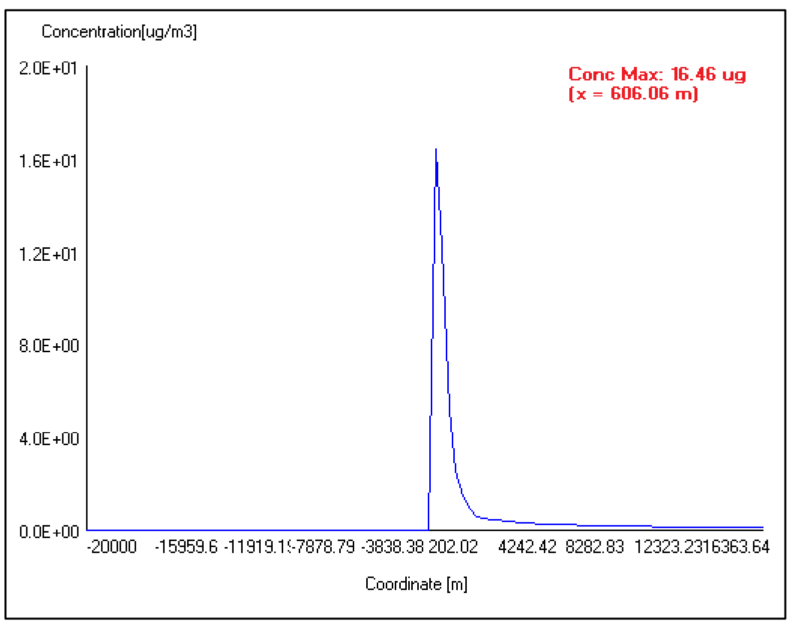


Figure 21. Cross sectional pollutant (Sulfur Dioxide) concentration as a function of downrange distance x (Classification A)

The stack is located at the position of 0 m.

Gaussian Plume Dispersion - Class B

The input parameters and output results for atmospheric classification 'B' are stated in Table 7. Figure 22 demonstrates the visual representation for atmospheric condition *B* up to downwind range of 20 km. Maximum chemical concentration of 9.80 ug/m^3 is calculated at a range of 3 km from stack in the downwind direction. Screen3 provides a maximum concentration of 10.24 ug/m^3 at a range of 2.424 km while METI-LIS provides maximum concentration of 13.49 ug/m^3 SO_2 at a range of 1.818 km.

Table 7. Gaussian plume dispersion table for atmospheric condition B.

```
***THESIS PROJECT OUTPUT***
Input:
Medium            Gas
Emission     (g/s)28.85
Exit Vel     (m/s)18.31
Exit Temp    (K  )372.04
U10          (m/s)3.0
U10 Temp     (K  )281.01
Stack Height (m  )30.48

Output;
Receptor Height:0m   Geography: Rural   Atm-Classification: B   Wind Velocity-Stk(h): 3.24
```

x	Conc ug/m3	Stack-Eff (H)	Stack_Eff (x)	Buoyancy	Momentuem	SD(y)	SD(z)
0	0.01	419.27	1213.78	true	false	82.75	51.09
1	0.55	419.27	1213.78	true	false	154.12	109.30
2	8.49	419.27	1213.78	true	false	285.80	233.82
3	9.80	419.27	1213.78	true	false	409.22	364.81
4	7.55	419.27	1213.78	true	false	527.31	500.20
5	5.57	419.27	1213.78	true	false	641.47	638.94
6	4.17	419.27	1213.78	true	false	752.50	780.42
7	3.21	419.27	1213.78	true	false	860.93	924.22
8	2.53	419.27	1213.78	true	false	967.15	1070.04
9	2.05	419.27	1213.78	true	false	1071.44	1217.64
10	1.68	419.27	1213.78	true	false	1174.01	1366.85
11	1.41	419.27	1213.78	true	false	1275.04	1517.51
12	1.20	419.27	1213.78	true	false	1374.67	1669.51
13	1.03	419.27	1213.78	true	false	1473.03	1822.75
14	0.89	419.27	1213.78	true	false	1570.20	1977.14
15	0.78	419.27	1213.78	true	false	1666.28	2132.60
16	0.69	419.27	1213.78	true	false	1761.34	2289.08
17	0.61	419.27	1213.78	true	false	1855.44	2446.50
18	0.55	419.27	1213.78	true	false	1948.64	2604.83
19	0.50	419.27	1213.78	true	false	2041.00	2764.02
20	0.45	419.27	1213.78	true	false	2132.55	2924.02

Output has been validated using Screen3 EPA Model (Table 8).

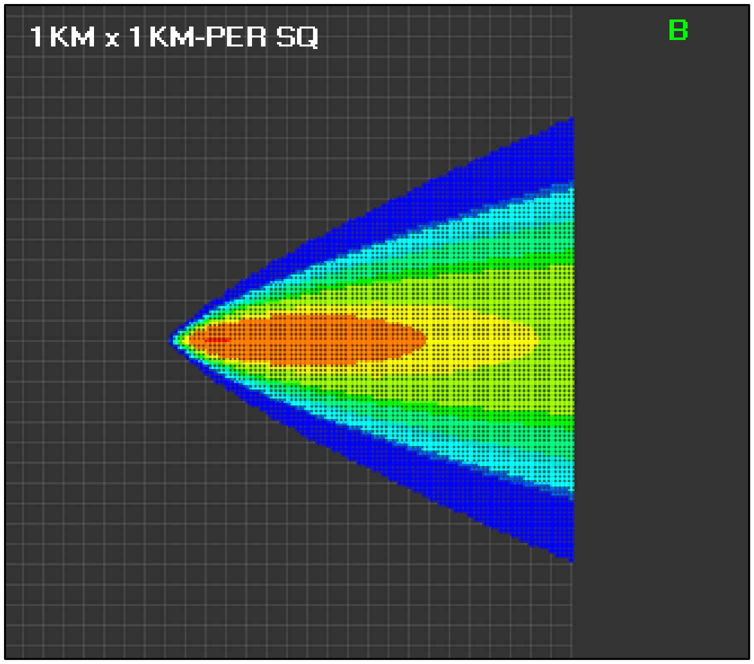


Figure 22. Visual representation of pollutant concentration for atmospheric condition B up to downwind range of 20 km.

Screen3 Validation (Class - B)

Table 8. Screen3 model output for atmospheric classification 'B'.

➔ Note: Input parameters are the same as in Table 7.

```
***********************************
*** SCREEN AUTOMATED DISTANCES ***
***********************************

*** TERRAIN HEIGHT OF    0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***

  DIST      CONC            U10M   USTK  MIX HT   PLUME   SIGMA   SIGMA
   (M)   (UG/M**3)   STAB   (M/S)  (M/S)   (M)    HT (M)   Y (M)   Z (M)  DWASH
-------  ----------  ----   -----  -----  ------  ------  ------  ------  -----
     1.    0.000       2     3.0    3.2   960.0  419.25    3.67    3.66    NO
   100.    0.000       2     3.0    3.2   960.0  419.25   28.52   23.55    NO
   200.    0.000       2     3.0    3.2   960.0  419.25   49.22   39.04    NO
   300.   0.2347E-10   2     3.0    3.2   960.0  419.25   68.11   53.13    NO
   400.   0.1091E-05   2     3.0    3.2   960.0  419.25   85.96   66.40    NO
   500.   0.3672E-03   2     3.0    3.2   960.0  419.25  103.10   79.95    NO
   600.   0.1060E-01   2     3.0    3.2   960.0  419.25  119.70   93.36    NO
   700.   0.8674E-01   2     3.0    3.2   960.0  419.25  135.87  106.70    NO
   800.   0.3476       2     3.0    3.2   960.0  419.25  151.68  119.99    NO
   900.   0.9018       2     3.0    3.2   960.0  419.25  167.19  133.27    NO
  1000.    1.769       2     3.0    3.2   960.0  419.25  182.43  146.55    NO
  1100.    2.876       2     3.0    3.2   960.0  419.25  197.45  159.83    NO
  1200.    4.106       2     3.0    3.2   960.0  419.25  212.25  173.13    NO
  1300.    5.031       2     3.0    3.2   960.0  419.25  224.25  183.26    NO
  1400.    5.900       2     3.0    3.2   960.0  419.25  235.90  193.22    NO
  1500.    6.732       2     3.0    3.2   960.0  419.25  247.62  203.52    NO
  1600.    7.497       2     3.0    3.2   960.0  419.25  259.38  214.11    NO
  1700.    8.175       2     3.0    3.2   960.0  419.25  271.17  224.97    NO
  1800.    8.756       2     3.0    3.2   960.0  419.25  282.98  236.06    NO
  1900.    9.234       2     3.0    3.2   960.0  419.25  294.80  247.37    NO
  2000.    9.610       2     3.0    3.2   960.0  419.25  306.62  258.86    NO
  2100.    9.891       2     3.0    3.2   960.0  419.25  318.44  270.53    NO
  2200.    10.08       2     3.0    3.2   960.0  419.25  330.25  282.36    NO
  2300.    10.20       2     3.0    3.2   960.0  419.25  342.04  294.33    NO
  2400.    10.24       2     3.0    3.2   960.0  419.25  353.82  306.43    NO
  2500.    10.23       2     3.0    3.2   960.0  419.25  365.58  318.66    NO
  2600.    10.17       2     3.0    3.2   960.0  419.25  377.32  331.00    NO
  2700.    10.06       2     3.0    3.2   960.0  419.25  389.03  343.45    NO
  2800.    9.923       2     3.0    3.2   960.0  419.25  400.72  355.99    NO
  2900.    9.760       2     3.0    3.2   960.0  419.25  412.39  368.63    NO
  3000.    9.576       2     3.0    3.2   960.0  419.25  424.02  381.35    NO
  3500.    8.516       2     3.0    3.2   960.0  419.25  481.80  446.08    NO
  4000.    7.478       2     3.0    3.2   960.0  419.25  538.88  512.38    NO
  4500.    6.606       2     3.0    3.2   960.0  419.25  595.28  579.93    NO
  5000.    5.913       2     3.0    3.2   960.0  419.25  651.02  648.52    NO
  5500.    5.365       2     3.0    3.2   960.0  419.25  706.13  718.01    NO
  6000.    4.928       2     3.0    3.2   960.0  419.25  760.65  788.29    NO
  6500.    4.572       2     3.0    3.2   960.0  419.25  814.62  859.26    NO
  7000.    4.274       2     3.0    3.2   960.0  419.25  868.07  930.87    NO
  7500.    4.021       2     3.0    3.2   960.0  419.25  921.02 1003.07    NO
  8000.    3.800       2     3.0    3.2   960.0  419.25  973.51 1075.79    NO
  8500.    3.606       2     3.0    3.2   960.0  419.25 1025.56 1149.01    NO
  9000.    3.432       2     3.0    3.2   960.0  419.25 1077.18 1222.70    NO
  9500.    3.276       2     3.0    3.2   960.0  419.25 1128.41 1296.82    NO
 10000.    3.135       2     3.0    3.2   960.0  419.25 1179.25 1371.35    NO
 15000.    2.213       2     3.0    3.2   960.0  419.25 1669.98 2135.49    NO
 20000.    1.731       2     3.0    3.2   960.0  419.25 2135.45 2926.13    NO
ITERATING TO FIND MAXIMUM CONCENTRATION . . .

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND     1. M:
  2424.    10.24       2     3.0    3.2   960.0  419.25  356.53  309.24    NO
```

METI-LIS Validation (Class - B)

METI-LIS provides maximum concentration of 13.49 ug/m^3 at a range of 1.818 km.

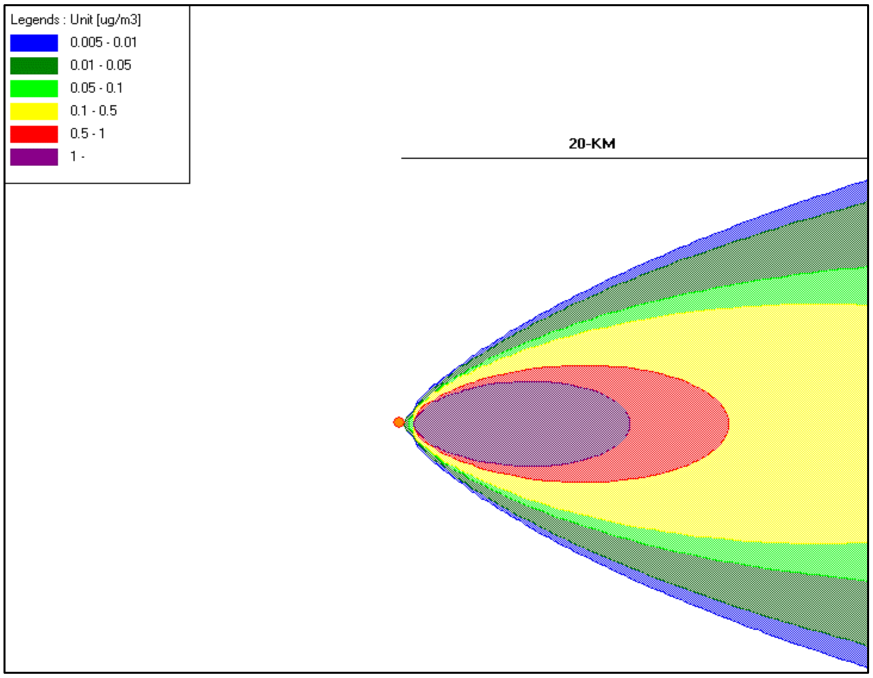


Figure 23. METI-LIS Visual representation of pollutant concentration for condition B.

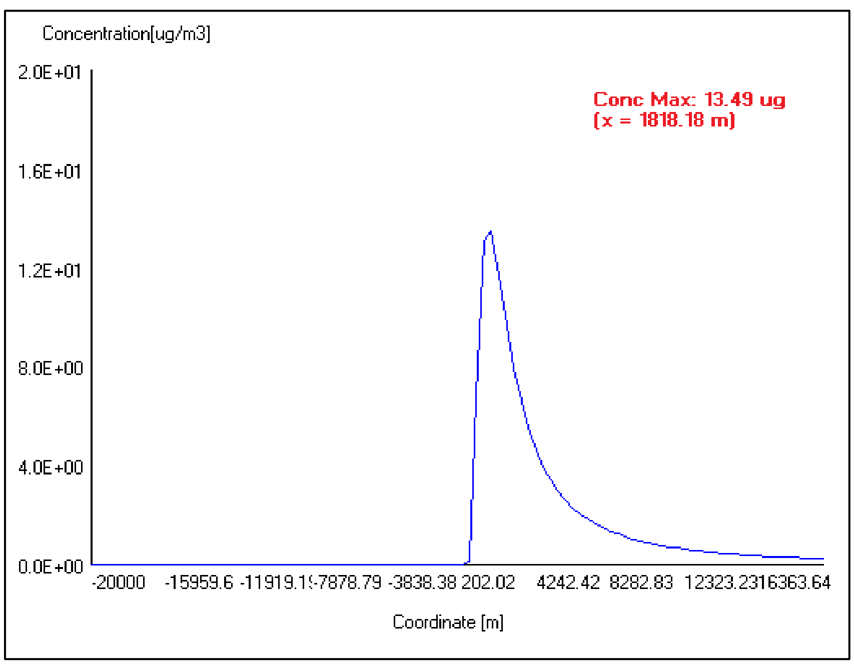


Figure 24. Cross sectional pollutant (Sulfur Dioxide) concentration as a function of downrange distance x (Classification B)

Gaussian Plume Dispersion - Class C

The input parameters and output results for atmospheric classification ‘C’ are stated in Table 9. Figure 25 demonstrates the visual representation for atmospheric condition *C* up to a downwind range of 20 km. A maximum chemical concentration of 8.30 ug/m^3 is calculated at a range of 6 km from the stack in a downwind direction. Screen3 provides maximum concentration of 7.714 ug/m^3 at a range of 4.879 km while METI-LIS provides maximum concentration of 11.18 ug/m^3 SO_2 at a range of 3.030 km.

Table 9. Gaussian plume dispersion table for atmospheric condition C.

```
***THESIS PROJECT OUTPUT***
Input:
Medium             Gas
Emission     (g/s)28.85
Exit Vel     (m/s)18.31
Exit Temp    (K  )372.04
U10          (m/s)3.0
U10 Temp     (K  )281.01
Stack Height (m  )30.48

Output;
Receptor Height:0m   Geography: Rural   Atm-Classification: C   Wind Velocity-Stk(h): 3.35
```

x	Conc ug/m3	Stack-Eff (H)	Stack_Eff (x)	Buoyancy	Momentuem	SD(y)	SD(z)
0	0.00	406.48	1213.78	true	false	56.91	32.43
1	0.00	406.48	1213.78	true	false	103.11	61.14
2	0.26	406.48	1213.78	true	false	185.01	115.26
3	3.27	406.48	1213.78	true	false	259.02	167.01
4	6.68	406.48	1213.78	true	false	327.94	217.27
5	8.17	406.48	1213.78	true	false	393.09	266.47
6	8.30	406.48	1213.78	true	false	455.22	314.82
7	7.82	406.48	1213.78	true	false	514.87	362.49
8	7.14	406.48	1213.78	true	false	572.38	409.58
9	6.43	406.48	1213.78	true	false	628.03	456.17
10	5.76	406.48	1213.78	true	false	682.03	502.32
11	5.17	406.48	1213.78	true	false	734.54	548.08
12	4.64	406.48	1213.78	true	false	785.71	593.48
13	4.19	406.48	1213.78	true	false	835.63	638.56
14	3.80	406.48	1213.78	true	false	884.42	683.34
15	3.45	406.48	1213.78	true	false	932.14	727.85
16	3.15	406.48	1213.78	true	false	978.89	772.11
17	2.89	406.48	1213.78	true	false	1024.70	816.14
18	2.66	406.48	1213.78	true	false	1069.65	859.94
19	2.46	406.48	1213.78	true	false	1113.77	903.53
20	2.28	406.48	1213.78	true	false	1157.12	946.93

Output table has been validated using Screen3 EPA Model (Table 10).

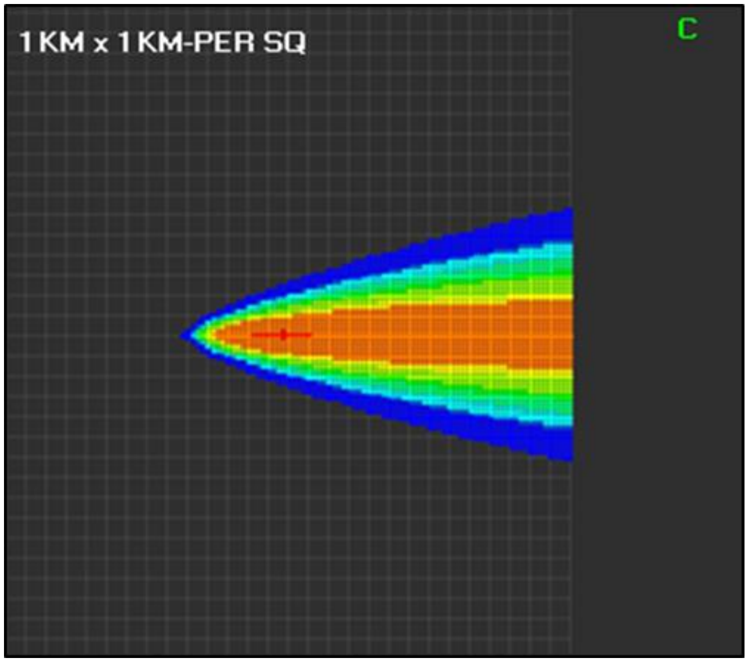


Figure 25. Visual representation of pollutant concentration for atmospheric condition C up to downwind range of 20 km.

Screen 3 Validation (Class - C)

Table 10. Screen3 model output for atmospheric classification ‘C’.

➔ Note: Input parameters are the same as in Table 9.

```
 ***********************************
 *** SCREEN AUTOMATED DISTANCES ***
 ***********************************

 *** TERRAIN HEIGHT OF    0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***

   DIST     CONC             U10M   USTK  MIX HT   PLUME   SIGMA   SIGMA
   (M)    (UG/M**3)   STAB  (M/S)  (M/S)   (M)    HT (M)   Y (M)   Z (M)  DWASH
 -------  ----------  ----  -----  -----  ------  ------  ------  ------  -----
     1.    0.000        3     3.0    3.4   960.0  406.46    3.55    3.55    NO
   100.    0.000        3     3.0    3.4   960.0  406.46   23.85   21.66    NO
   200.    0.000        3     3.0    3.4   960.0  406.46   40.00   35.20    NO
   300.   0.5576E-13    3     3.0    3.4   960.0  406.46   54.46   46.94    NO
   400.   0.1144E-07    3     3.0    3.4   960.0  406.46   67.97   57.67    NO
   500.   0.7607E-05    3     3.0    3.4   960.0  406.46   80.85   67.74    NO
   600.   0.3793E-03    3     3.0    3.4   960.0  406.46   93.26   77.32    NO
   700.   0.4850E-02    3     3.0    3.4   960.0  406.46  105.30   86.52    NO
   800.   0.2813E-01    3     3.0    3.4   960.0  406.46  117.04   95.42    NO
   900.   0.9951E-01    3     3.0    3.4   960.0  406.46  128.53  104.06    NO
  1000.   0.2542        3     3.0    3.4   960.0  406.46  139.80  112.48    NO
  1100.   0.5187        3     3.0    3.4   960.0  406.46  150.89  120.71    NO
  1200.   0.9023        3     3.0    3.4   960.0  406.46  161.80  128.78    NO
  1300.    1.111        3     3.0    3.4   960.0  406.46  169.33  132.59    NO
  1400.    1.300        3     3.0    3.4   960.0  406.46  176.47  135.86    NO
  1500.    1.511        3     3.0    3.4   960.0  406.46  183.73  139.24    NO
  1600.    1.741        3     3.0    3.4   960.0  406.46  191.09  142.73    NO
  1700.    1.988        3     3.0    3.4   960.0  406.46  198.54  146.31    NO
  1800.    2.252        3     3.0    3.4   960.0  406.46  206.06  149.98    NO
  1900.    2.530        3     3.0    3.4   960.0  406.46  213.64  153.73    NO
  2000.    2.818        3     3.0    3.4   960.0  406.46  221.27  157.56    NO
  2100.    3.114        3     3.0    3.4   960.0  406.46  228.94  161.44    NO
  2200.    3.415        3     3.0    3.4   960.0  406.46  236.65  165.39    NO
  2300.    3.717        3     3.0    3.4   960.0  406.46  244.38  169.39    NO
  2400.    4.019        3     3.0    3.4   960.0  406.46  252.14  173.44    NO
  2500.    4.317        3     3.0    3.4   960.0  406.46  259.92  177.54    NO
  2600.    4.609        3     3.0    3.4   960.0  406.46  267.71  181.68    NO
  2700.    4.893        3     3.0    3.4   960.0  406.46  275.52  185.85    NO
  2800.    5.166        3     3.0    3.4   960.0  406.46  283.33  190.06    NO
  2900.    5.428        3     3.0    3.4   960.0  406.46  291.15  194.30    NO
  3000.    5.677        3     3.0    3.4   960.0  406.46  298.97  198.57    NO
  3500.    6.700        3     3.0    3.4   960.0  406.46  338.08  220.26    NO
  4000.    7.343        3     3.0    3.4   960.0  406.46  377.09  242.38    NO
  4500.    7.653        3     3.0    3.4   960.0  406.46  415.92  264.76    NO
  5000.    7.708        3     3.0    3.4   960.0  406.46  454.51  287.31    NO
  5500.    7.586        3     3.0    3.4   960.0  406.46  492.86  309.95    NO
  6000.    7.349        3     3.0    3.4   960.0  406.46  530.96  332.65    NO
  6500.    7.044        3     3.0    3.4   960.0  406.46  568.81  355.36    NO
  7000.    6.705        3     3.0    3.4   960.0  406.46  606.40  378.08    NO
  7500.    6.354        3     3.0    3.4   960.0  406.46  643.75  400.77    NO
  8000.    6.007        3     3.0    3.4   960.0  406.46  680.87  423.44    NO
  8500.    5.674        3     3.0    3.4   960.0  406.46  717.76  446.07    NO
  9000.    5.359        3     3.0    3.4   960.0  406.46  754.43  468.65    NO
  9500.    5.066        3     3.0    3.4   960.0  406.46  790.88  491.19    NO
 10000.    4.797        3     3.0    3.4   960.0  406.46  827.14  513.68    NO
 15000.    3.109        3     3.0    3.4   960.0  406.46 1179.90  735.74    NO
 20000.    2.363        3     3.0    3.4   960.0  406.46 1518.37  953.01    NO
 ITERATING TO FIND MAXIMUM CONCENTRATION . . .

 MAXIMUM 1-HR CONCENTRATION AT OR BEYOND     1. M:
  4879.    7.714        3     3.0    3.4   960.0  406.46  445.12  281.79    NO
```

METI-LIS Validation (Class - C)

METI-LIS provides maximum concentration of 11.18 ug/m^3 at a range of 3.030 km.

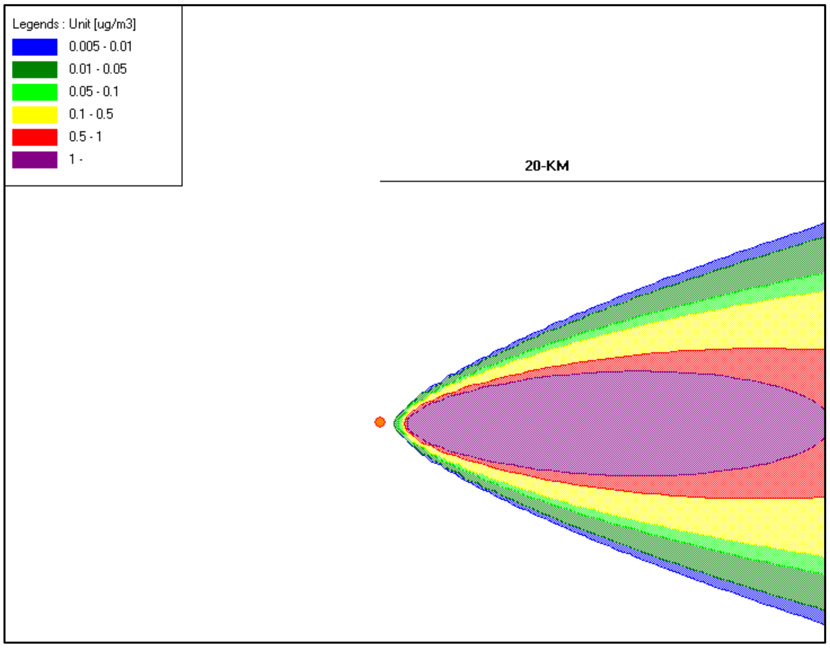


Figure 26. METI-LIS Visual representation of pollutant concentration for condition C

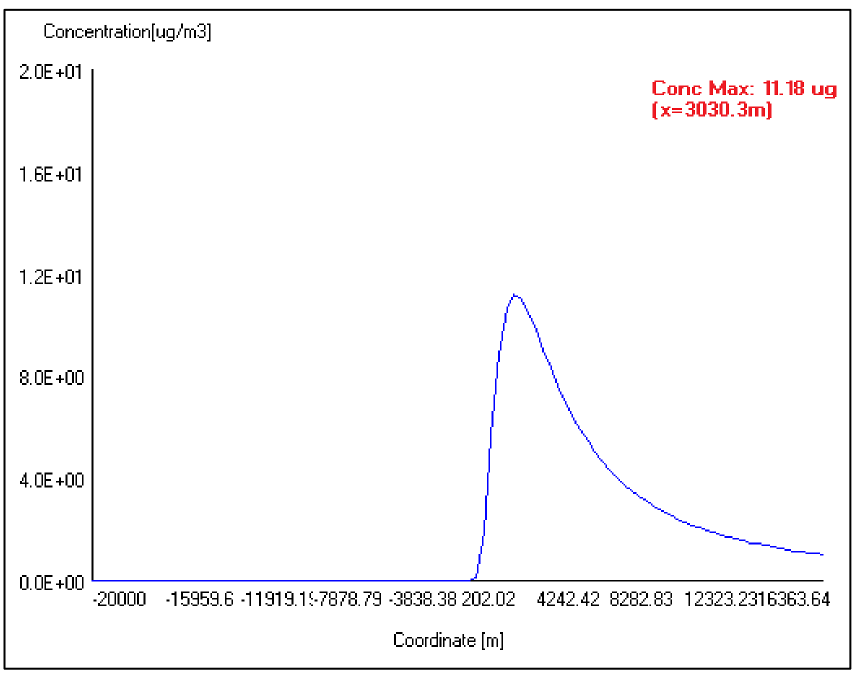


Figure 27. Cross sectional pollutant (Sulfur Dioxide) concentration as a function of downrange distance x (Classification C)

Gaussian Plume Dispersion - Class D

The input parameters and output results for atmospheric classification ‘D’ are stated in Table 11. Figure 28 demonstrates the visual representation for atmospheric condition *D* up to a downwind range of 20 km. A maximum chemical concentration of 1.99 ug/m^3 is calculated at a range of 20 km from the stack in a downwind direction. Screen3 provides maximum concentration of 2.593 ug/m^3 at a range of 20.250 km while METI-LIS provides maximum concentration of 4.718 ug/m^3 SO_2 at a range of 11.11 km.

Table 11. Gaussian plume dispersion table for atmospheric condition D.

```
***THESIS PROJECT OUTPUT***
Input:
Medium              Gas
Emission     (g/s)28.85
Exit Vel     (m/s)18.31
Exit Temp    (K  )372.04
U10          (m/s)3.0
U10 Temp     (K  )281.01
Stack Height (m  )30.48

Output;
Receptor Height:0m   Geography: Rural   Atm-Classification: D   Wind Velocity-Stk(h): 3.55
```

x	Conc ug/m3	Stack-Eff (H)	Stack_Eff (x)	Buoyancy	Momentuem	SD(y)	SD(z)
0	0.00	386.10	1213.78	true	false	36.15	18.30
1	0.00	386.10	1213.78	true	false	68.13	32.09
2	0.00	386.10	1213.78	true	false	127.94	50.15
3	0.00	386.10	1213.78	true	false	184.64	65.12
4	0.00	386.10	1213.78	true	false	239.31	77.49
5	0.01	386.10	1213.78	true	false	292.47	88.69
6	0.04	386.10	1213.78	true	false	344.44	99.03
7	0.11	386.10	1213.78	true	false	395.41	108.71
8	0.23	386.10	1213.78	true	false	445.53	117.85
9	0.39	386.10	1213.78	true	false	494.90	126.56
10	0.59	386.10	1213.78	true	false	543.62	134.88
11	0.78	386.10	1213.78	true	false	591.73	142.36
12	0.97	386.10	1213.78	true	false	639.31	149.54
13	1.15	386.10	1213.78	true	false	686.39	156.47
14	1.32	386.10	1213.78	true	false	733.02	163.18
15	1.47	386.10	1213.78	true	false	779.22	169.67
16	1.61	386.10	1213.78	true	false	825.03	175.98
17	1.73	386.10	1213.78	true	false	870.46	182.13
18	1.83	386.10	1213.78	true	false	915.55	188.11
19	1.92	386.10	1213.78	true	false	960.30	193.96
20	1.99	386.10	1213.78	true	false	1004.75	199.67

Output has been validated using Screen3 EPA Model (Table 12).

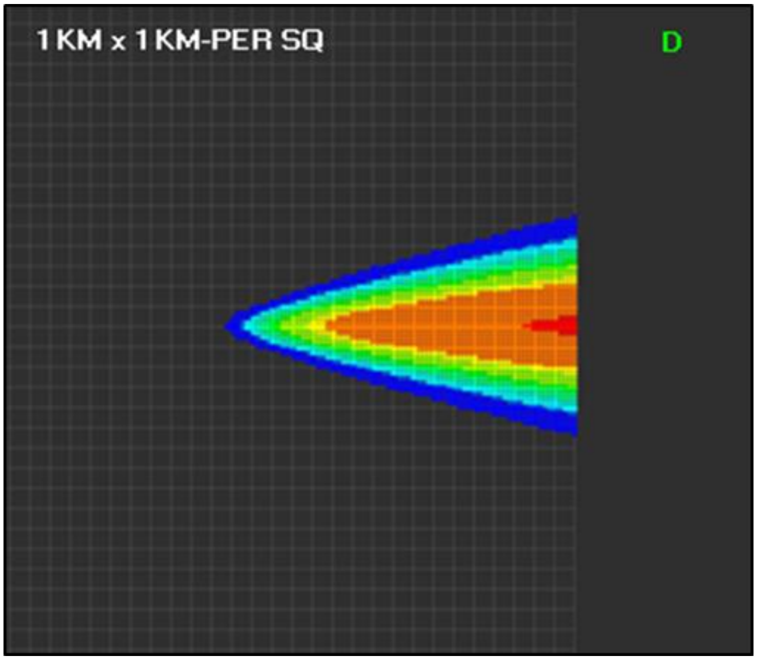


Figure 28. Visual representation of pollutant concentration for atmospheric condition D up to downwind range of 20 km.

Screen3 Validation (Class - D)

Table 12. Screen3 model output for atmospheric classification ‘D’.

➔ Note: Input parameters are the same as in Table 11.

```
***********************************
*** SCREEN AUTOMATED DISTANCES ***
***********************************

*** TERRAIN HEIGHT OF    0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***
```

DIST (M)	CONC (UG/M**3)	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
1.	0.000	4	3.0	3.5	960.0	386.09	3.37	3.37	NO
100.	0.000	4	3.0	3.5	960.0	386.09	20.91	19.79	NO
200.	0.000	4	3.0	3.5	960.0	386.09	34.27	31.70	NO
300.	0.000	4	3.0	3.5	960.0	386.09	45.96	41.80	NO
400.	0.2642E-09	4	3.0	3.5	960.0	386.09	56.72	50.82	NO
500.	0.3672E-06	4	3.0	3.5	960.0	386.09	66.86	59.15	NO
600.	0.3061E-04	4	3.0	3.5	960.0	386.09	76.55	66.97	NO
700.	0.5727E-03	4	3.0	3.5	960.0	386.09	85.88	74.38	NO
800.	0.4456E-02	4	3.0	3.5	960.0	386.09	94.92	81.48	NO
900.	0.1994E-01	4	3.0	3.5	960.0	386.09	103.72	88.30	NO
1000.	0.6170E-01	4	3.0	3.5	960.0	386.09	112.31	94.88	NO
1100.	0.1442	4	3.0	3.5	960.0	386.09	120.73	101.08	NO
1200.	0.2824	4	3.0	3.5	960.0	386.09	128.99	107.10	NO
1300.	0.3176	4	3.0	3.5	960.0	386.09	133.45	108.48	NO
1400.	0.3310	4	3.0	3.5	960.0	386.09	137.44	109.14	NO
1500.	0.3448	4	3.0	3.5	960.0	386.09	141.54	109.81	NO
1600.	0.3592	4	3.0	3.5	960.0	386.09	145.75	110.50	NO
1700.	0.3740	4	3.0	3.5	960.0	386.09	150.04	111.19	NO
1800.	0.3892	4	3.0	3.5	960.0	386.09	154.42	111.89	NO
1900.	0.4050	4	3.0	3.5	960.0	386.09	158.87	112.59	NO
2000.	0.4213	4	3.0	3.5	960.0	386.09	163.38	113.31	NO
2100.	0.4380	4	3.0	3.5	960.0	386.09	167.95	114.02	NO
2200.	0.4552	4	3.0	3.5	960.0	386.09	172.56	114.75	NO
2300.	0.4729	4	3.0	3.5	960.0	386.09	177.23	115.47	NO
2400.	0.4911	4	3.0	3.5	960.0	386.09	181.93	116.21	NO
2500.	0.5098	4	3.0	3.5	960.0	386.09	186.66	116.94	NO
2600.	0.5289	4	3.0	3.5	960.0	386.09	191.43	117.68	NO
2700.	0.5485	4	3.0	3.5	960.0	386.09	196.23	118.43	NO
2800.	0.5685	4	3.0	3.5	960.0	386.09	201.05	119.17	NO
2900.	0.5890	4	3.0	3.5	960.0	386.09	205.89	119.92	NO
3000.	0.6099	4	3.0	3.5	960.0	386.09	210.75	120.68	NO
3500.	0.7080	4	3.0	3.5	960.0	386.09	235.26	124.23	NO
4000.	0.8118	4	3.0	3.5	960.0	386.09	259.98	127.78	NO
4500.	0.9198	4	3.0	3.5	960.0	386.09	284.80	131.33	NO
5000.	1.030	4	3.0	3.5	960.0	386.09	309.62	134.87	NO
5500.	1.142	4	3.0	3.5	960.0	386.09	334.40	138.38	NO
6000.	1.254	4	3.0	3.5	960.0	386.09	359.11	141.88	NO
6500.	1.364	4	3.0	3.5	960.0	386.09	383.73	145.35	NO
7000.	1.472	4	3.0	3.5	960.0	386.09	408.25	148.80	NO
7500.	1.576	4	3.0	3.5	960.0	386.09	432.67	152.21	NO
8000.	1.677	4	3.0	3.5	960.0	386.09	456.97	155.60	NO
8500.	1.773	4	3.0	3.5	960.0	386.09	481.15	158.96	NO
9000.	1.865	4	3.0	3.5	960.0	386.09	505.22	162.29	NO
9500.	1.951	4	3.0	3.5	960.0	386.09	529.18	165.59	NO
10000.	2.032	4	3.0	3.5	960.0	386.09	553.03	168.87	NO
15000.	2.479	4	3.0	3.5	960.0	386.09	785.82	197.77	NO
20000.	2.593	4	3.0	3.5	960.0	386.09	1009.87	224.03	NO

ITERATING TO FIND MAXIMUM CONCENTRATION . . .

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 1. M:

20250.	2.593	4	3.0	3.5	960.0	386.09	1020.92	225.30	NO

METI-LIS Validation (Class - D)

METI-LIS provides maximum concentration of 4.718 ug/m^3 at a range of 11.111 km.

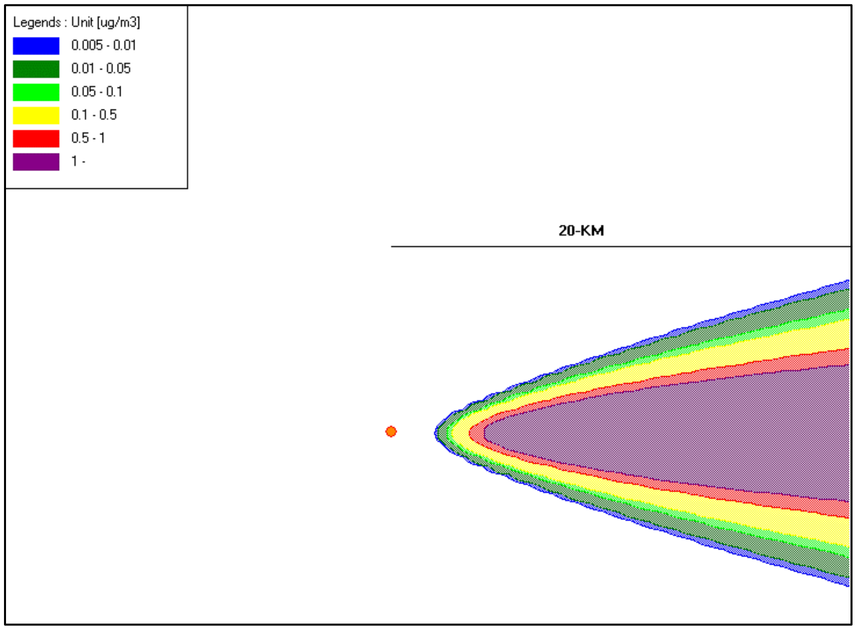


Figure 29. METI-LIS Visual representation of pollutant concentration for condition D

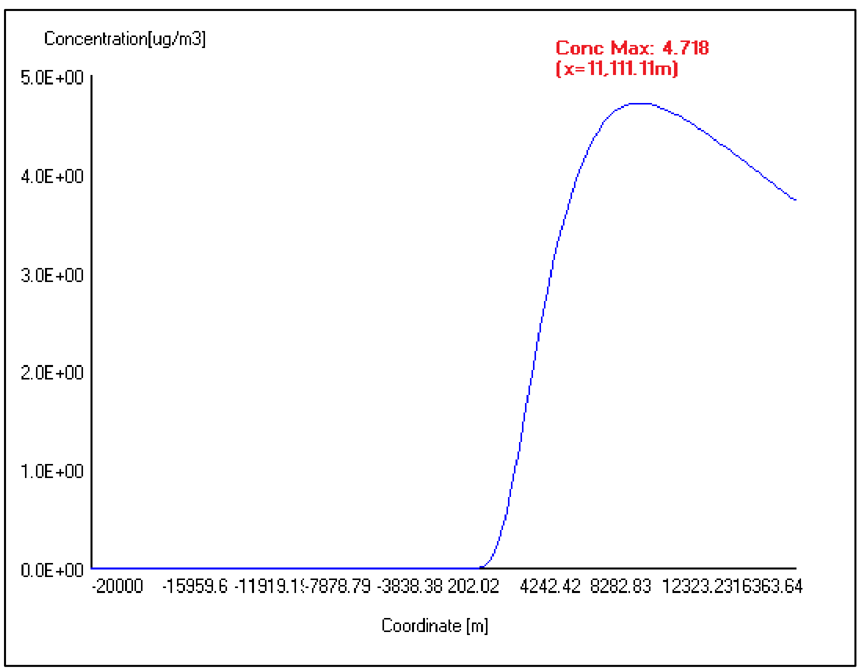


Figure 30. Cross sectional pollutant (Sulfur Dioxide) concentration as a function of downrange distance x (Classification D)

Gaussian Plume Dispersion - Class E

The input parameters and output results for atmospheric classification 'E' are stated in Table 13. Figure 31 demonstrates the visual representation for atmospheric condition E up to a downwind range of 20 km. A maximum chemical concentration of 10.22 ug/m^3 is calculated at a range of 13 km from the stack in a downwind direction. Screen3 provides a maximum concentration of 12.03 ug/m^3 at a range of 10 km while METI-LIS provides a maximum concentration of 2.76 ug/m^3 SO_2 at a range of 20 km.

Table 13. Gaussian plume dispersion table for atmospheric condition E

```
***THESIS PROJECT OUTPUT***
Input:
Medium             Gas
Emission     (g/s)28.85
Exit Vel     (m/s)18.31
Exit Temp    (K  )372.04
U10          (m/s)3.0
U10 Temp     (K  )281.01
Stack Height (m  )30.48

Output;
Receptor Height:0m   Geography: Rural   Atm-Classification: E   Wind Velocity-Stk(h): 4.43

x     Conc ug/m3   Stack-Eff   Stack_Eff  Buoyancy Momentuem SD(y)   SD(z)
                      (H)         (x)
0       0.00       154.03      347.45     true     false     27.02    12.80
1       0.00       154.03      347.45     true     false     50.94    21.63
2       0.02       154.03      347.45     true     false     95.70    33.49
3       0.46       154.03      347.45     true     false     138.13    42.22
4       1.93       154.03      347.45     true     false     179.06    49.77
5       3.72       154.03      347.45     true     false     218.86    55.71
6       5.48       154.03      347.45     true     false     257.77    61.08
7       6.98       154.03      347.45     true     false     295.94    66.03
8       8.16       154.03      347.45     true     false     333.47    70.64
9       9.04       154.03      347.45     true     false     370.44    74.97
10      9.66       154.03      347.45     true     false     406.92    79.07
11      9.98       154.03      347.45     true     false     442.96    82.67
12      10.15       154.03      347.45     true     false     478.59    86.10
13      10.22       154.03      347.45     true     false     513.86    89.38
14      10.21       154.03      347.45     true     false     548.78    92.53
15      10.14       154.03      347.45     true     false     583.39    95.56
16      10.03       154.03      347.45     true     false     617.70    98.48
17      9.88       154.03      347.45     true     false     651.73    101.31
18      9.71       154.03      347.45     true     false     685.50    104.05
19      9.53       154.03      347.45     true     false     719.03    106.71
20      9.34       154.03      347.45     true     false     752.32    109.30
```

Output table has been validated using Screen3 EPA Model (Table 14).

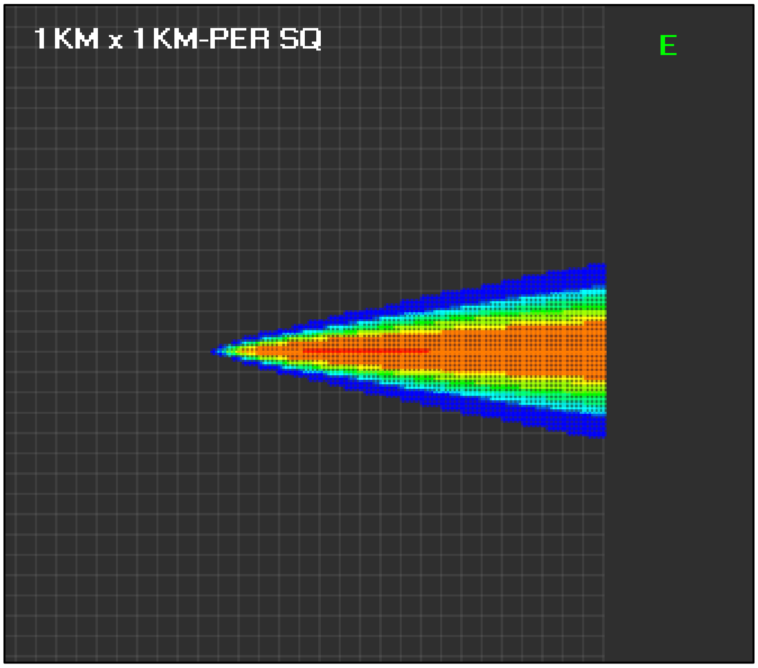


Figure 31. Visual representation of pollutant concentration for atmospheric condition E up to downwind range of 20 km.

Screen3 Validation (Class - E)

Table 14. Screen3 model output for atmospheric classification 'E'

➔ Note: Input parameters are the same as in Table 13.

```
***********************************
*** SCREEN AUTOMATED DISTANCES ***
***********************************

*** TERRAIN HEIGHT OF    0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***
```

DIST (M)	CONC (UG/M**3)	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
1.	0.000	5	3.0	4.4	10000.0	154.08	2.74	2.74	NO
100.	0.000	5	3.0	4.4	10000.0	154.08	16.57	15.79	NO
200.	0.2384E-04	5	3.0	4.4	10000.0	154.08	27.06	25.22	NO
300.	0.3584E-01	5	3.0	4.4	10000.0	154.08	36.20	33.18	NO
400.	0.2241	5	3.0	4.4	10000.0	154.08	41.61	36.93	NO
500.	0.2755	5	3.0	4.4	10000.0	154.08	44.46	37.56	NO
600.	0.3408	5	3.0	4.4	10000.0	154.08	47.61	38.25	NO
700.	0.4227	5	3.0	4.4	10000.0	154.08	50.98	38.98	NO
800.	0.5240	5	3.0	4.4	10000.0	154.08	54.53	39.76	NO
900.	0.6475	5	3.0	4.4	10000.0	154.08	58.20	40.57	NO
1000.	0.7960	5	3.0	4.4	10000.0	154.08	61.98	41.41	NO
1100.	0.9301	5	3.0	4.4	10000.0	154.08	65.84	42.13	NO
1200.	1.079	5	3.0	4.4	10000.0	154.08	69.75	42.85	NO
1300.	1.242	5	3.0	4.4	10000.0	154.08	73.71	43.57	NO
1400.	1.421	5	3.0	4.4	10000.0	154.08	77.70	44.30	NO
1500.	1.613	5	3.0	4.4	10000.0	154.08	81.72	45.02	NO
1600.	1.821	5	3.0	4.4	10000.0	154.08	85.76	45.75	NO
1700.	2.042	5	3.0	4.4	10000.0	154.08	89.81	46.48	NO
1800.	2.276	5	3.0	4.4	10000.0	154.08	93.87	47.21	NO
1900.	2.522	5	3.0	4.4	10000.0	154.08	97.94	47.94	NO
2000.	2.781	5	3.0	4.4	10000.0	154.08	102.01	48.67	NO
2100.	3.012	5	3.0	4.4	10000.0	154.08	106.08	49.32	NO
2200.	3.249	5	3.0	4.4	10000.0	154.08	110.15	49.98	NO
2300.	3.490	5	3.0	4.4	10000.0	154.08	114.22	50.62	NO
2400.	3.736	5	3.0	4.4	10000.0	154.08	118.28	51.27	NO
2500.	3.984	5	3.0	4.4	10000.0	154.08	122.35	51.91	NO
2600.	4.235	5	3.0	4.4	10000.0	154.08	126.40	52.54	NO
2700.	4.488	5	3.0	4.4	10000.0	154.08	130.46	53.17	NO
2800.	4.742	5	3.0	4.4	10000.0	154.08	134.50	53.80	NO
2900.	4.996	5	3.0	4.4	10000.0	154.08	138.54	54.42	NO
3000.	5.251	5	3.0	4.4	10000.0	154.08	142.58	55.04	NO
3500.	6.501	5	3.0	4.4	10000.0	154.08	162.63	58.08	NO
4000.	7.680	5	3.0	4.4	10000.0	154.08	182.51	61.02	NO
4500.	8.526	5	3.0	4.4	10000.0	154.08	202.19	63.54	NO
5000.	9.258	5	3.0	4.4	10000.0	154.08	221.69	65.96	NO
5500.	9.881	5	3.0	4.4	10000.0	154.08	241.02	68.30	NO
6000.	10.40	5	3.0	4.4	10000.0	154.08	260.18	70.56	NO
6500.	10.83	5	3.0	4.4	10000.0	154.08	279.18	72.75	NO
7000.	11.18	5	3.0	4.4	10000.0	154.08	298.04	74.88	NO
7500.	11.46	5	3.0	4.4	10000.0	154.08	316.75	76.95	NO
8000.	11.67	5	3.0	4.4	10000.0	154.08	335.33	78.98	NO
8500.	11.82	5	3.0	4.4	10000.0	154.08	353.79	80.95	NO
9000.	11.93	5	3.0	4.4	10000.0	154.08	372.12	82.87	NO
9500.	12.00	5	3.0	4.4	10000.0	154.08	390.34	84.76	NO
10000.	12.03	5	3.0	4.4	10000.0	154.08	408.45	86.60	NO
15000.	11.09	5	3.0	4.4	10000.0	154.08	584.45	101.87	NO
20000.	9.743	5	3.0	4.4	10000.0	154.08	753.15	114.87	NO

```
ITERATING TO FIND MAXIMUM CONCENTRATION . . .

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND     1. M:
 10000.     12.03        5     3.0     4.4 10000.0   154.08   408.45    86.60     NO
```

METI-LIS Validation (Class - E)

METI-LIS provides maximum concentration of 2.76 ug/m^3 at a range of 20.00 km.

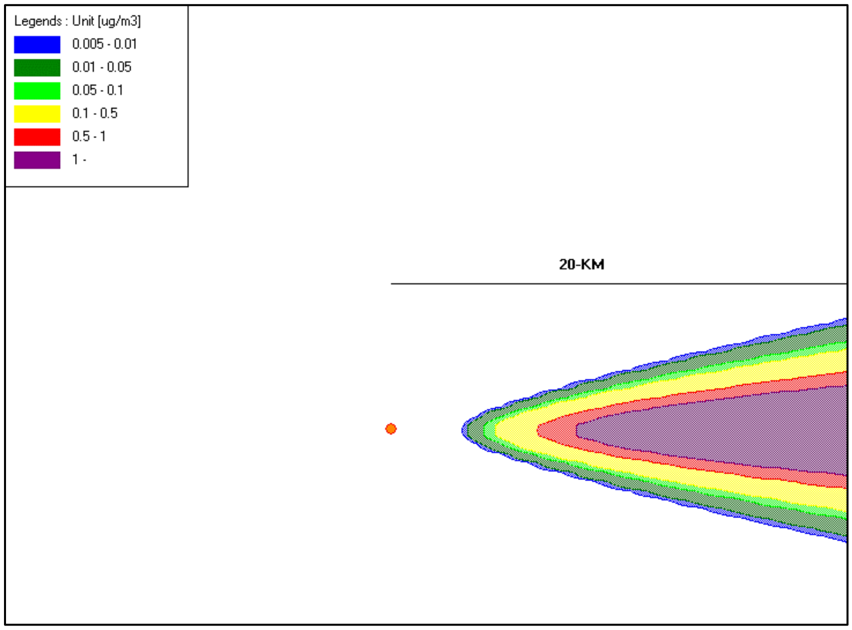


Figure 32. METI-LIS Visual representation of pollutant concentration for condition E

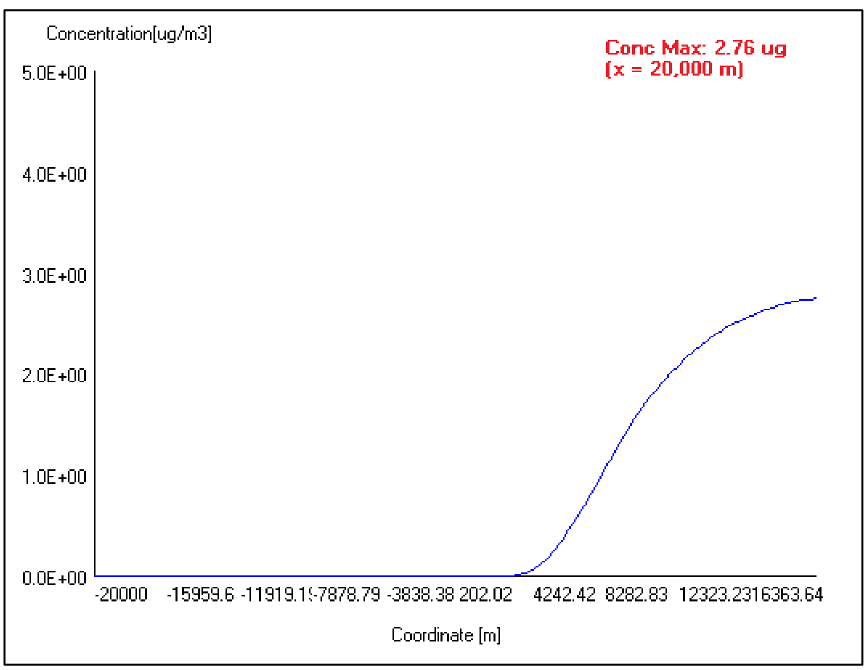


Figure 33. Cross sectional pollutant (Sulfur Dioxide) concentration as a function of downrange distance x (Classification E)

Gaussian Plume Dispersion - Class F

The input parameters and output results for atmospheric classification 'F' are stated in Table 15. Figure 34 demonstrates the visual representation for atmospheric condition F up to a downwind range of 20 km. A maximum chemical concentration of 6.26 ug/m^3 is calculated at a range of 20 km from the stack in a downwind direction. Screen3 provides a maximum concentration of 8.468 ug/m^3 at a range of 15 km, while METI-LIS provides a maximum concentration of 0.5459 ug/m^3 SO_2 at a range of 20 km.

Table 15. Gaussian plume dispersion table for atmospheric condition F.

```
***THESIS PROJECT OUTPUT***
Input:
Medium             Gas
Emission     (g/s)28.85
Exit Vel     (m/s)18.31
Exit Temp    (K  )372.04
U10          (m/s)3.0
U10 Temp     (K  )281.01
Stack Height (m  )30.48

Output;
Receptor Height:0m   Geography: Rural   Atm-Classification: F   Wind Velocity-Stk(h): 5.54
```

x	Conc ug/m3	Stack-Eff (H)	Stack_Eff (x)	Buoyancy	Momentuem	SD(y)	SD(z)
0	0.00	125.67	248.89	true	false	17.97	8.40
1	0.00	125.67	248.89	true	false	33.88	13.95
2	0.00	125.67	248.89	true	false	63.68	21.63
3	0.01	125.67	248.89	true	false	91.92	26.98
4	0.11	125.67	248.89	true	false	119.17	30.84
5	0.39	125.67	248.89	true	false	145.67	34.21
6	0.87	125.67	248.89	true	false	171.58	37.23
7	1.51	125.67	248.89	true	false	196.99	40.00
8	2.13	125.67	248.89	true	false	221.98	42.28
9	2.76	125.67	248.89	true	false	246.61	44.40
10	3.36	125.67	248.89	true	false	270.90	46.38
11	3.92	125.67	248.89	true	false	294.90	48.26
12	4.44	125.67	248.89	true	false	318.63	50.03
13	4.90	125.67	248.89	true	false	342.12	51.72
14	5.30	125.67	248.89	true	false	365.38	53.34
15	5.66	125.67	248.89	true	false	388.43	54.89
16	5.83	125.67	248.89	true	false	411.28	56.05
17	5.97	125.67	248.89	true	false	433.95	57.18
18	6.09	125.67	248.89	true	false	456.44	58.25
19	6.18	125.67	248.89	true	false	478.77	59.29
20	6.26	125.67	248.89	true	false	500.95	60.29

Output has been validated using Screen3 EPA Model (Table 16).

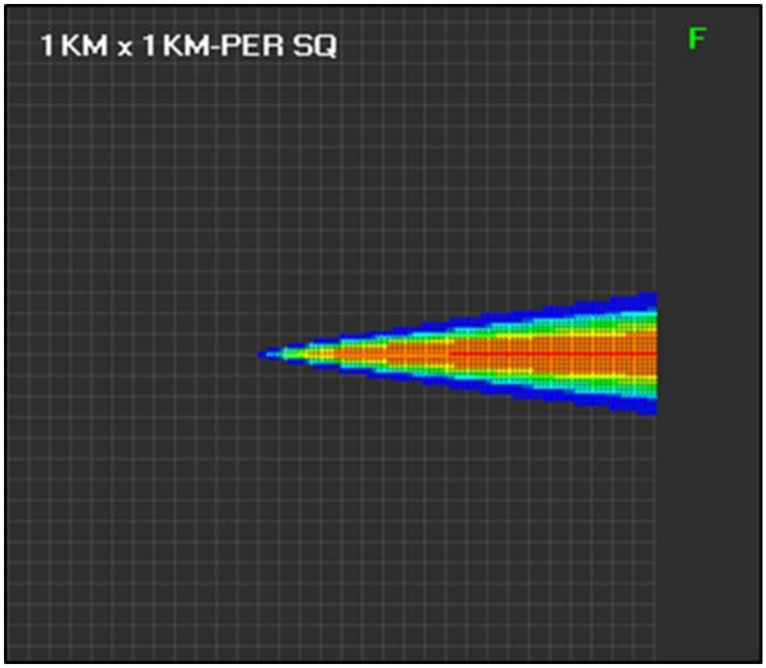


Figure 34. Visual representation of pollutant concentration for atmospheric condition F up to downwind range of 20 km.

Screen 3 Validation (Class-F)

Table 16. Screen3 model output for atmospheric classification 'F'

➔ Note: Input parameters are the same as in Table 15.

*** TERRAIN HEIGHT OF 0. M ABOVE STACK BASE USED FOR FOLLOWING DISTANCES ***

DIST (M)	CONC (UG/M**3)	STAB	U10M (M/S)	USTK (M/S)	MIX HT (M)	PLUME HT (M)	SIGMA Y (M)	SIGMA Z (M)	DWASH
1.	0.000	6	3.0	5.5	10000.0	125.70	2.21	2.21	NO
100.	0.000	6	3.0	5.5	10000.0	125.70	12.97	12.54	NO
200.	0.9981E-05	6	3.0	5.5	10000.0	125.70	21.03	19.98	NO
300.	0.2334E-01	6	3.0	5.5	10000.0	125.70	27.98	26.23	NO
400.	0.8650E-01	6	3.0	5.5	10000.0	125.70	30.89	28.10	NO
500.	0.1046	6	3.0	5.5	10000.0	125.70	32.60	28.47	NO
600.	0.1279	6	3.0	5.5	10000.0	125.70	34.51	28.88	NO
700.	0.1577	6	3.0	5.5	10000.0	125.70	36.58	29.32	NO
800.	0.1883	6	3.0	5.5	10000.0	125.70	38.78	29.73	NO
900.	0.2244	6	3.0	5.5	10000.0	125.70	41.08	30.14	NO
1000.	0.2667	6	3.0	5.5	10000.0	125.70	43.45	30.58	NO
1100.	0.3104	6	3.0	5.5	10000.0	125.70	45.90	30.98	NO
1200.	0.3597	6	3.0	5.5	10000.0	125.70	48.39	31.39	NO
1300.	0.4150	6	3.0	5.5	10000.0	125.70	50.92	31.80	NO
1400.	0.4766	6	3.0	5.5	10000.0	125.70	53.48	32.22	NO
1500.	0.5449	6	3.0	5.5	10000.0	125.70	56.07	32.64	NO
1600.	0.6201	6	3.0	5.5	10000.0	125.70	58.68	33.06	NO
1700.	0.7025	6	3.0	5.5	10000.0	125.70	61.31	33.48	NO
1800.	0.7923	6	3.0	5.5	10000.0	125.70	63.94	33.90	NO
1900.	0.8897	6	3.0	5.5	10000.0	125.70	66.59	34.33	NO
2000.	0.9948	6	3.0	5.5	10000.0	125.70	69.24	34.75	NO
2100.	1.086	6	3.0	5.5	10000.0	125.70	71.90	35.12	NO
2200.	1.181	6	3.0	5.5	10000.0	125.70	74.56	35.48	NO
2300.	1.280	6	3.0	5.5	10000.0	125.70	77.23	35.85	NO
2400.	1.383	6	3.0	5.5	10000.0	125.70	79.89	36.20	NO
2500.	1.490	6	3.0	5.5	10000.0	125.70	82.56	36.56	NO
2600.	1.600	6	3.0	5.5	10000.0	125.70	85.22	36.92	NO
2700.	1.714	6	3.0	5.5	10000.0	125.70	87.89	37.27	NO
2800.	1.832	6	3.0	5.5	10000.0	125.70	90.55	37.62	NO
2900.	1.952	6	3.0	5.5	10000.0	125.70	93.21	37.97	NO
3000.	2.076	6	3.0	5.5	10000.0	125.70	95.86	38.31	NO
3500.	2.576	6	3.0	5.5	10000.0	125.70	109.10	39.75	NO
4000.	3.086	6	3.0	5.5	10000.0	125.70	122.24	41.12	NO
4500.	3.595	6	3.0	5.5	10000.0	125.70	135.27	42.44	NO
5000.	4.095	6	3.0	5.5	10000.0	125.70	148.19	43.71	NO
5500.	4.578	6	3.0	5.5	10000.0	125.70	161.01	44.93	NO
6000.	5.041	6	3.0	5.5	10000.0	125.70	173.72	46.11	NO
6500.	5.479	6	3.0	5.5	10000.0	125.70	186.34	47.26	NO
7000.	5.894	6	3.0	5.5	10000.0	125.70	198.86	48.38	NO
7500.	6.198	6	3.0	5.5	10000.0	125.70	211.30	49.34	NO
8000.	6.478	6	3.0	5.5	10000.0	125.70	223.65	50.28	NO
8500.	6.733	6	3.0	5.5	10000.0	125.70	235.91	51.19	NO
9000.	6.967	6	3.0	5.5	10000.0	125.70	248.10	52.07	NO
9500.	7.179	6	3.0	5.5	10000.0	125.70	260.22	52.93	NO
10000.	7.372	6	3.0	5.5	10000.0	125.70	272.27	53.77	NO
15000.	8.468	6	3.0	5.5	10000.0	125.70	389.38	61.26	NO
20000.	8.214	6	3.0	5.5	10000.0	125.70	501.69	66.15	NO

ITERATING TO FIND MAXIMUM CONCENTRATION . . .

MAXIMUM 1-HR CONCENTRATION AT OR BEYOND 1. M:

14999.	8.468	6	3.0	5.5	10000.0	125.70	389.38	61.26	NO

METI-LIS Validation (Class - F)

METI-LIS provides maximum concentration of 0.5459 ug/m^3 at a range of 20.00 km.

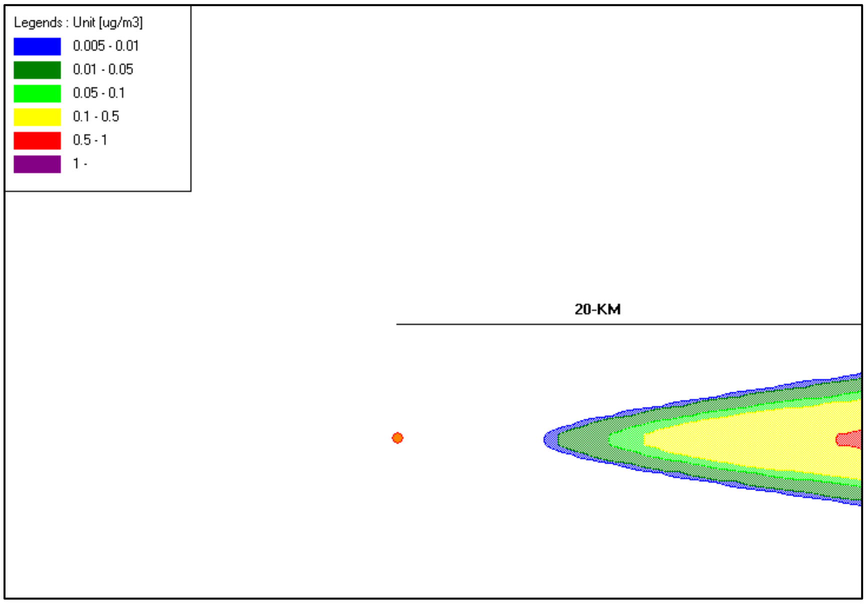


Figure 35. METI-LIS Visual representation of pollutant concentration for condition F

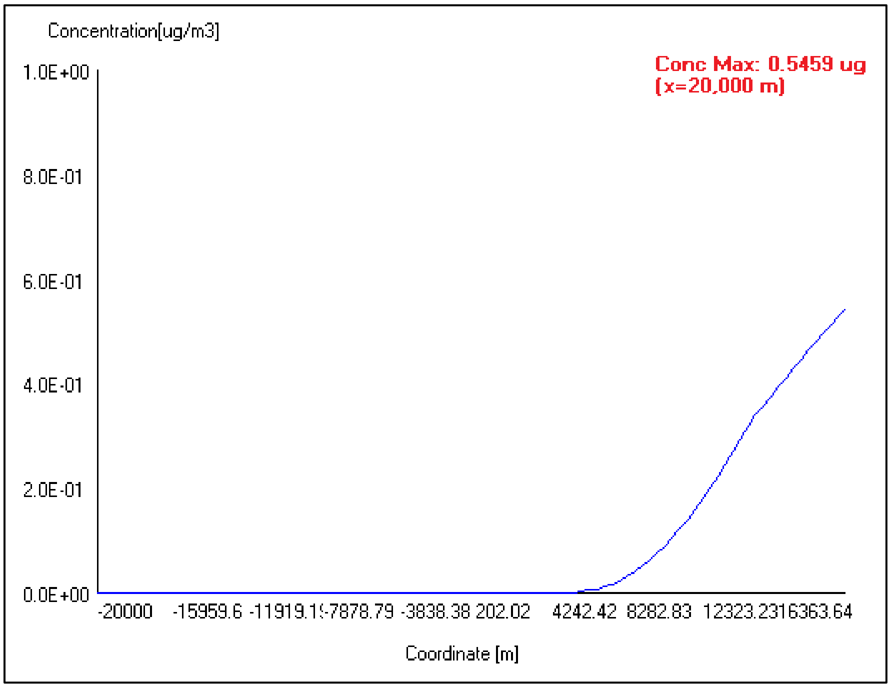


Figure 36. Cross sectional pollutant (Sulfur Dioxide) concentration as a function of downrange distance x (Classification F)

Plume Interaction

The spatial positioning of coal power plants, depending upon meteorological conditions, can result in ‘plume interaction’ phenomena. Plume interaction is simply pollutants sharing the same spatial volume for pollutants exhausted by multiple sources. Plume interaction is important given that an individual source of interest may be spreading pollutants below the EPA threshold, however, the presence of multiple sources and their resultant interaction can end up driving local concentrations higher than the EPA threshold.

Per problem 20 on page 52 of the EPA - Workbook of Atmospheric Dispersion Estimates, the final concentration of SO_2 on a given receptor point is obtained by summation of individual pollutant concentrate emitted from a power plant and refinery at that given receptor point (Turner, 1970).

The same strategy is being applied in our simulation, where two coal power plants emitting the same amount of SO_2 are tested for plume interaction, and then the final interacted concentration is checked against the EPA threshold. Tables 17 and 18 show the simulation output representing changes in pollutant concentration (ug/m^3) at ground level as a function of distance (kilometers) from the source in the down wind direction. Power plant (1) is considered as an existing operational coal power plant, while power plant (2) is the newcomer. Both power plant energy generation and pollution emission rates are exactly same.

Table 17. Plume concentration as a function of downwind range (kilometers) for Power plants (1) and (2), and their respective interaction (5 km distance between power plants 1 and 2)

➔ Note: Input parameters are the same as in Table 5.

x	Pwr.Plant 1 (ug/m3)	Pwr.Plant 2 (ug/m3)	Interaction (ug/m3)
0	15.651	15.651	15.651
1	21.530	21.442	21.442
2	3.684	3.684	3.684
3	1.113	1.113	1.113
4	0.805	0.805	0.805
5	0.664	0.664	0.664
6	0.567	0.567	0.567
7	0.497	0.497	0.497
8	0.443	0.443	0.444
9	0.401	0.401	0.402
10	0.366	0.366	0.368
11	0.338	0.338	0.342
12	0.314	0.314	0.320
13	0.293	0.293	0.303
14	0.275	0.275	0.289
15	0.260	0.260	0.278
16	0.246	0.246	0.269
17	0.234	0.234	0.261
18	0.223	0.223	0.255
19	0.213	0.213	0.249
20	0.204	0.204	0.244

Interaction Detected

In the above table, the '*Interaction'* column represents the Power plant (1) plume being detected against the Power plant (2) plume along a grid plane of ($x_{0:20(km)}$, $y_{0:0(km)}$). Both power plants are at the 5-km distance from each other along the y-axis as shown in Figure 37. It can be seen in Table 17 that the pollutant concentration in the '*Interaction*' column starts to gain value after the 8th kilometer.

A maximum chemical concentration of 21.510 ug/m^3 is calculated at a range of one kilometer from the stack in a downwind direction for each power plant. Along the Power plant (2) emission trail in the wind direction, the white line represents no plume interaction with Power plant (1), while the red line marks the plume interaction, which ranges from 8 km to 20 km. At the range of 20 km the pollutant concentration on the Power plant (2) emission trail is 19.60% higher than an individual power plant emission concentration.

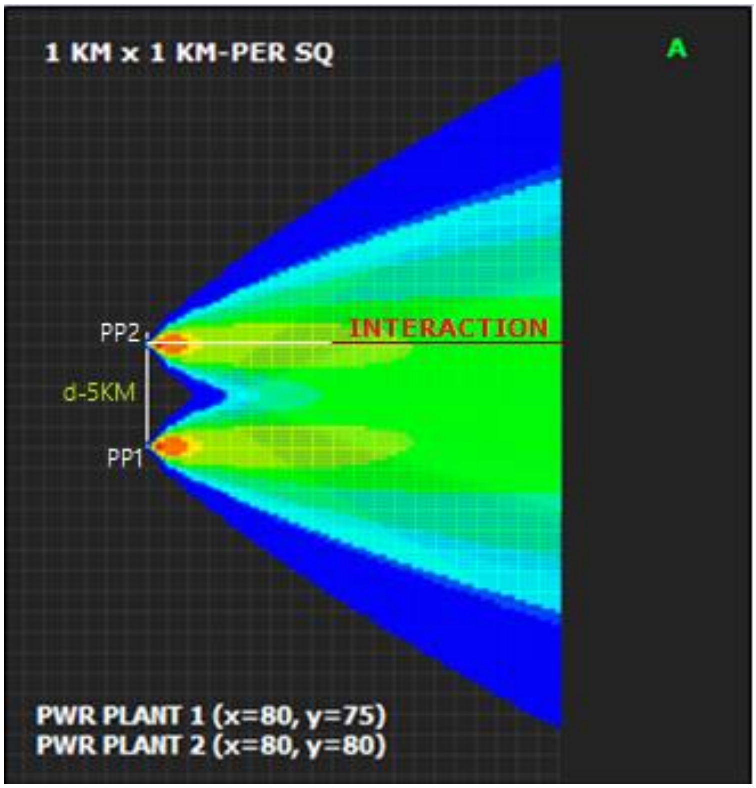


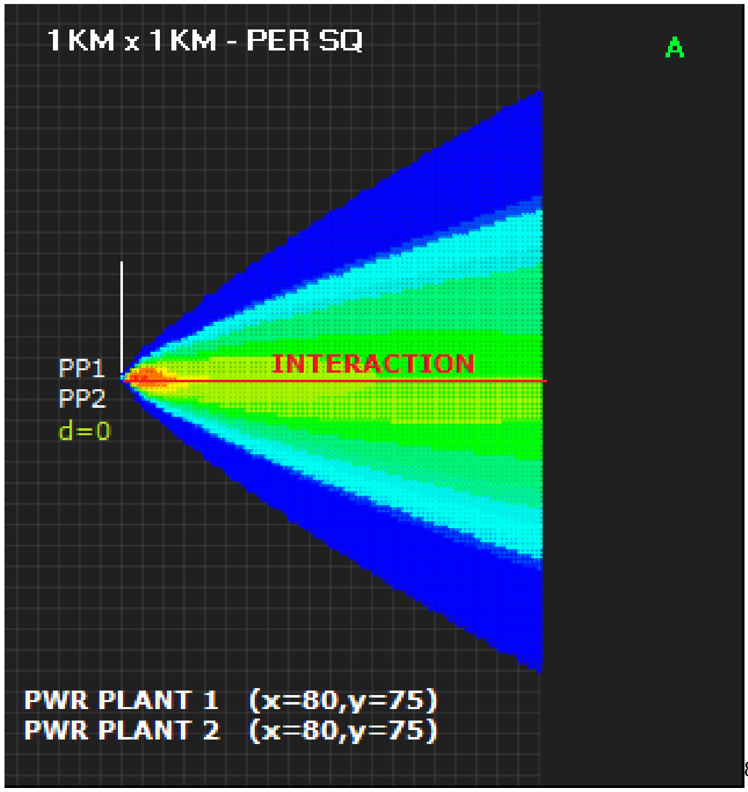
Figure 37. Plume interaction for Power plant (1) and Power plant (2) under atmospheric condition A up to downwind range of 20 km. 5 km distance between the Power plant (1) and (2).

Table 18. Plume concentration as a function of downwind range (kilometers) for Power plants (1) and (2), and their respective interaction. 0-km distance between Power plant (1) and (2).

➔ Note: Input parameters are the same as in Table 5.

x	Pwr.Plant 1 (ug/m3)	Pwr.Plant 2 (ug/m3)	Interaction (ug/m3)
0	15.651	15.651	31.302
1	21.530	21.442	42.972
2	3.684	3.684	7.368
3	1.113	1.113	2.225
4	0.805	0.805	1.610
5	0.664	0.664	1.328
6	0.567	0.567	1.135
7	0.497	0.497	0.994
8	0.443	0.443	0.887
9	0.401	0.401	0.802
10	0.366	0.366	0.733
11	0.338	0.338	0.676
12	0.314	0.314	0.628
13	0.293	0.293	0.586
14	0.275	0.275	0.551
15	0.260	0.260	0.520
16	0.246	0.246	0.492
17	0.234	0.234	0.468
18	0.223	0.223	0.446
19	0.213	0.213	0.426
20	0.204	0.204	0.408

In above Table 18, '*Interaction'* column also represents Power plant (1) plume being detected against Power plant (2) plume along a grid plane of ($x_{0:20(km)}$, $y_{0:0(km)}$). Both power plants are situated at the same location as shown in Figure 38. It can be seen in Table 18 that the pollutant concentration in the '*Interaction*' column, now has twice the value of the individual power plant pollutant concentration. A maximum chemical concentration of 42.972 ug/m^3 is calculated at a range of one kilometer from the stack in the downwind direction, due to interaction activity. At the range of 20 km, the pollutant concentration on Power plant (2) emission trail, is 200% higher than the individual power plant emission concentration.



[8]

Figure 38. Plume interaction for Power plant (1) and Power plant (2) under atmospheric condition A up to downwind range of 20 km. 0 km distance between power plants (1) and (2)

Resistive Losses

The Resistive Losses are calculated based on loss ratio. The 'Loss ratio' is defined as the ratio of power delivered to a given customer versus the initial power input to the system. The loss ratio is a function of resistance/meter, inductance/meter, and frequency of transmission line (Harting, 2010). Table 19 shows the loss ratio on a 1000 m aluminum transmission line with a conductivity value of $38.2_{x10}{}^{06}$ (S/m).

[8] Color scheme of contours are calculated based upon existing power plant minimum and maximum pollutant concentration range.

Table 19. (TOP) Resistance per meter as a function of skin depth and conductor radius. (BOTTOM) Loss Ratio as a function of resistance per meter and inductance per meter on 1000 m tranmission line.

Permability free space		1.2566E-06 H/m			
Metal conductivity (Al)		3.82E+07 S/m			
Line separation		10 m			
freq (Hz)	**Skin Depth (m)**	**Resistance/m**			
		Cond Radius **0.005**	Cond Radius **0.015**	Cond Radius **0.025**	Cond Radius **0.035**
1	0.08143	0.0000113	0.0000038	0.0000023	0.0000016
10	0.02575	0.0000356	0.0000119	0.0000071	0.0000051
60	0.01051	0.0000872	0.0000291	0.0000174	0.0000125
100	0.00814	0.0001126	0.0000375	0.0000225	0.0000161
1000	0.00258	0.0003560	0.0001187	0.0000712	0.0000509
10000	0.00081	0.0011256	0.0003752	0.0002251	0.0001608
Inductance		0.0000030	0.0000026	0.0000024	0.0000023
freq (Hz)	**X-(Meters)**	**Loss Ratio**	**Loss Ratio**	**Loss Ratio**	**Loss Ratio**
1	**1000**	0.0000123	0.0000048	0.0000031	0.0000024
10		0.0000390	0.0000152	0.0000099	0.0000075
60		0.0000956	0.0000372	0.0000243	0.0000184
100		0.0001234	0.0000481	0.0000313	0.0000237
1000		0.0003902	0.0001521	0.0000990	0.0000749
10000		0.0012333	0.0004807	0.0003131	0.0002369

Figure 39 provides a graphical representation of resistance per meter *(y-axis)* as a function of conductor radius *(x-axis)* at various skin depths. Resistance per meter is inversely proportional to operating frequency due to the phenomena of skin depth, while directly proportional to the radius of transmission line. A wire with a radius of 0.005 m, operating at a frequency of 60 Hz, has resistance of 8.72_{x10}^{-05} ohms/m while a wire of 0.035 m radius has a resistance of 1.25_{x10}^{-05} ohms/m. There is a substantial 85.66% decrease in resistance.

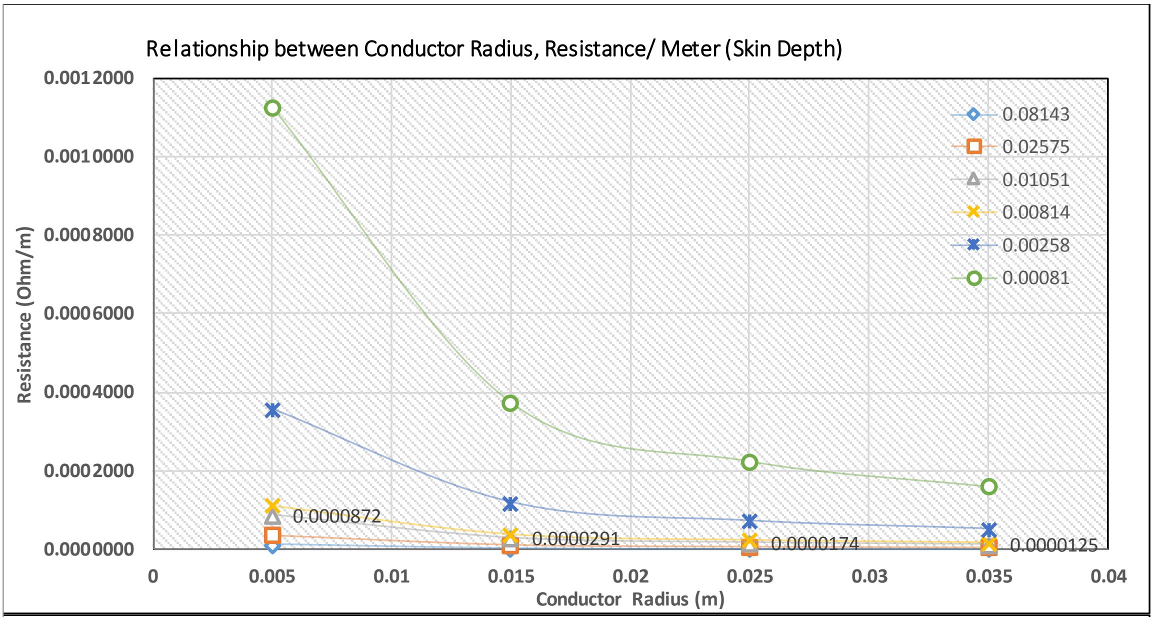


Figure 39. Graph representing change in resistance per meter (y-axis) as a function of conductor radius (x-axis)

Figure 40 provides a graphical representation of changes in 'Power Loss Ratio' (y-axis) as a function of conductor radius (x-axis) for a transmission line of 1000-m length, at various frequencies. Power loss is inversely proportional to operating frequency while directly proportional to the radius of the transmission line. A wire with a radius of 0.005 m, operating at a frequency of 60 Hz, has loss ratio of $9.56_{x10}{}^{-05}$ while a wire of 0.035 m radius has a resistance of $1.84_{x10}{}^{-05}$. A substantial 80.75% decrease in power loss.

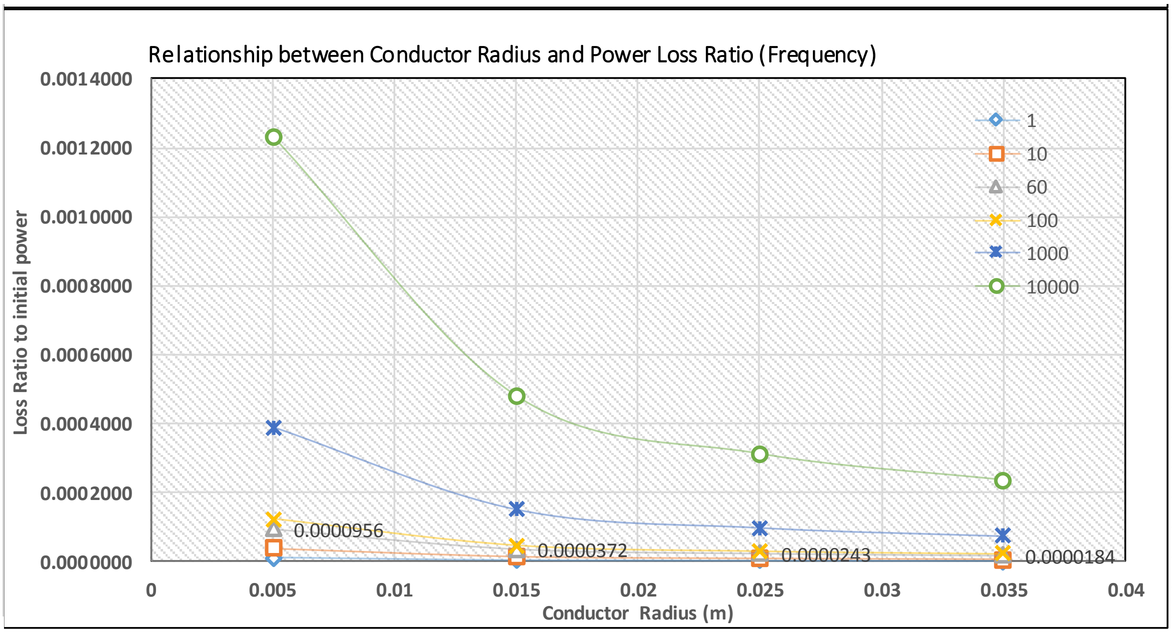


Figure 40. Graph representing change in ‘Power Loss Ratio’ (y-axis) as a function of conductor radius (x-axis)

Corona Losses

Corona Losses are energy losses due to ionization of air molecules in close proximity to a high voltage transmission line. Table 20 represents Corona Losses (kW/km/line) as a function of conductor radius (cm), and disruptive critical voltage (V) for a transmission line operating at a frequency of 60 Hz (Harting, 2010). Figure 42 represents change in Disruptive Critical Voltage (y-axis) as a function of conductor radius (x-axis).

ko, Fixed Constant	241	
go, Disruptive Gradient Voltage	21.1	kv/cm
d, Conductor Spacing	1000	cm
kd, Normal Air Density Factor	1	
ki, Wire Irregularity Factor	0.95	

			cm			
Conductor Radius			**0.5**	**1.5**	**2.5**	**3.5**
Disruptive Critical Voltage (KV)			76.18	195.51	300.25	396.74
freq	**Voltage**	**Vo, Line Voltage To Neutral**	**Corona Loss kW/Km/Line**			
	765	442.20	614	483	206	25
	400	231.21	110	10	49	332
	220	127.17	12	37	307	881
	110	63.58	1	138	574	1345
	66	38.15	7	196	704	1558
60	33	19.08	15	247	810	1729

Figure 41. Corona Losses in kW/km/line as a function of voltage and conductor radius

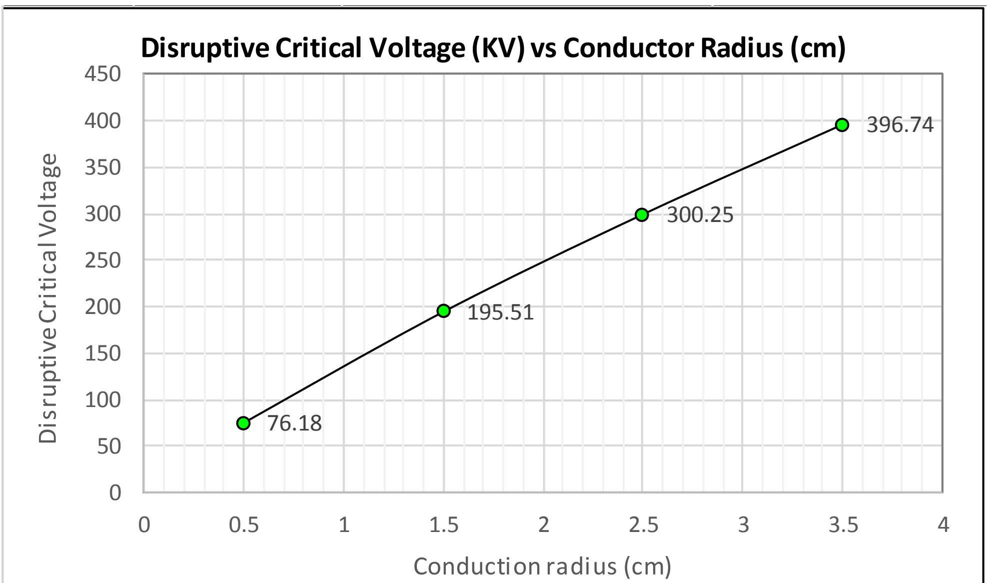


Figure 42. Graph representing relationship between *Disruptive Critical Voltage* and *Conductor Radius*

Figure 43 represents change in Corona Loss $_{\text{kW/km/line}}$ (y-axis) as a function of conductor radius (cm) at various Disruptive Critical Voltages (V). A disparity between conductor radius and disruptive critical voltage can result is higher than normal Corona Losses.

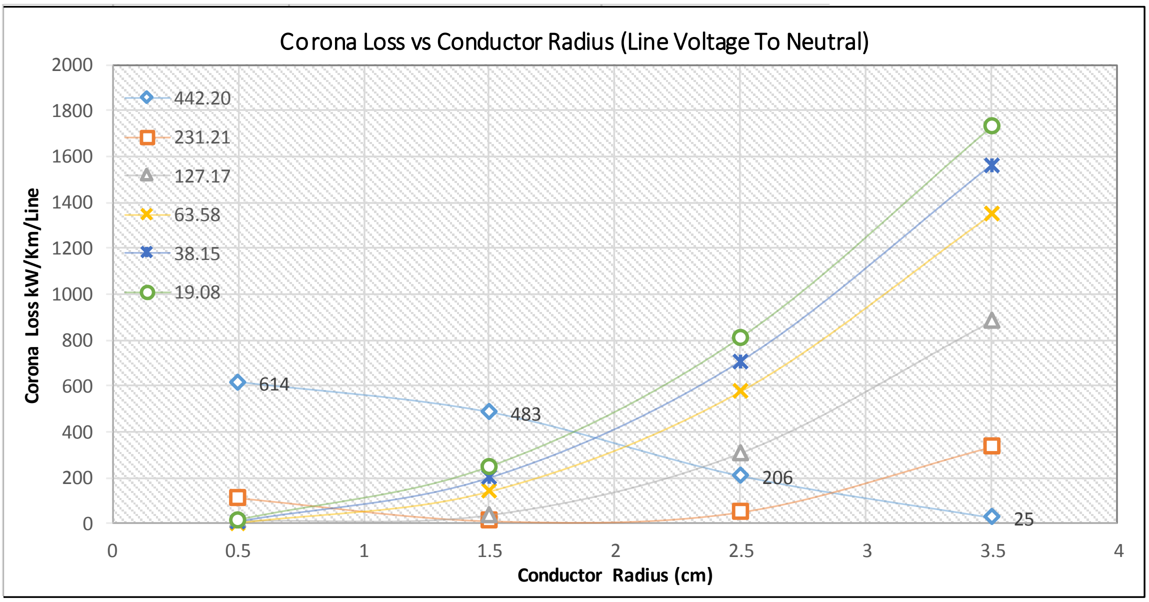


Figure 43. Corona Losses as a function of conductor radius at various 'Line voltages to Neutral'

Coal Transfer Cost

Coal transportation cost validation is done using a simplified model containing only one coal power plant and three coal mines as depicted in Figure 44. Total coal demand by a power plant is calculated using a simplified relationship. For every one megawatt-hour generated, a power plant consumes 0.733 tons of coal per hour (operating efficiency of a power plant affects this relationship). The *initial state* in Figure 44 represents initialization of simulation. Here the power plant is located at location of (x_0, y_0). Yellow lines represent the minimum spanning tree between the coal power plant and coal mines by application of Prim's algorithm. The power plant generation capacity is set at 884 MW, and each coal mine contributes 33.33% or 216 tons to the total coal demand. The transportation cost is set at $0.042 per ton-km. The coal movement and related costs are as follows:

1. 216 tons of coal get transferred from (Coalx-$_{80}$, Coaly-$_{45}$) location to (Coalx-$_{75}$, Coaly-$_{75}$) at a cost of $ 275.87.
2. 432 tons of coal gets transferred from (Coalx-$_{75}$, Coaly-$_{75}$) location to (Coalx-$_{55}$, Coaly-$_{65}$) at a cost of $ 405.69.
3. 648 tons of coal gets transferred from (Coalx-$_{55}$, Coaly-$_{65}$) location to (Power Plant x-$_{0}$, Power Plant y-$_{0}$) at a cost of $ 2,317.44.
4. Total cost to transfer all coal from three mines to the power plant is $2,999.

The *final state* in Figure 45 represents the conclusion of simulation. The optimal location for the power plant, which minimizes the total cost of coal transportation, is finalized at (x_{69}, y_{65}). The total transportation cost for coal delivery to the power plant is now $439.49, and delivery distance is 48.49 km, compared to Figure 44 which was $2,999, and delivery distance of 137 km.

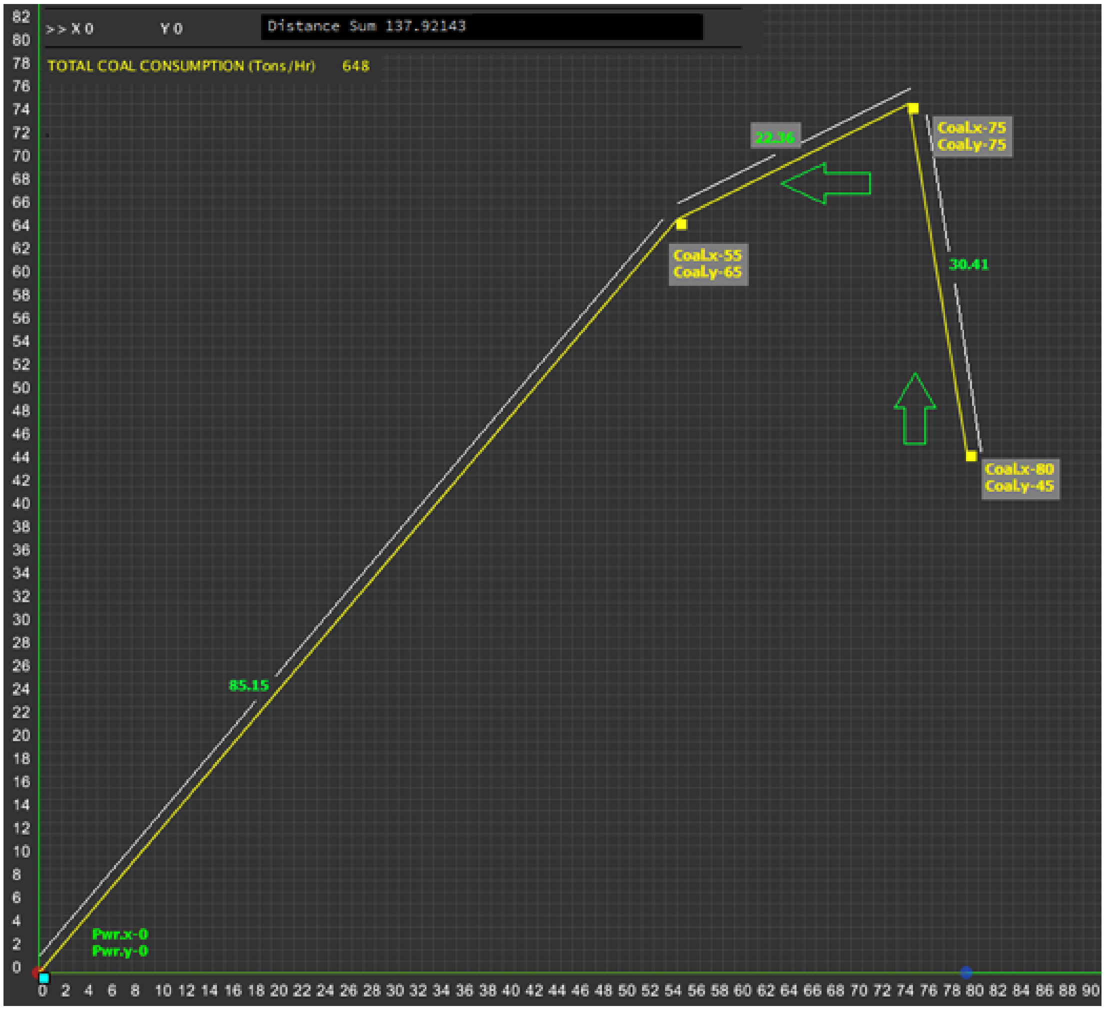


Figure 44. Coal transportation cost validation (Initial State)

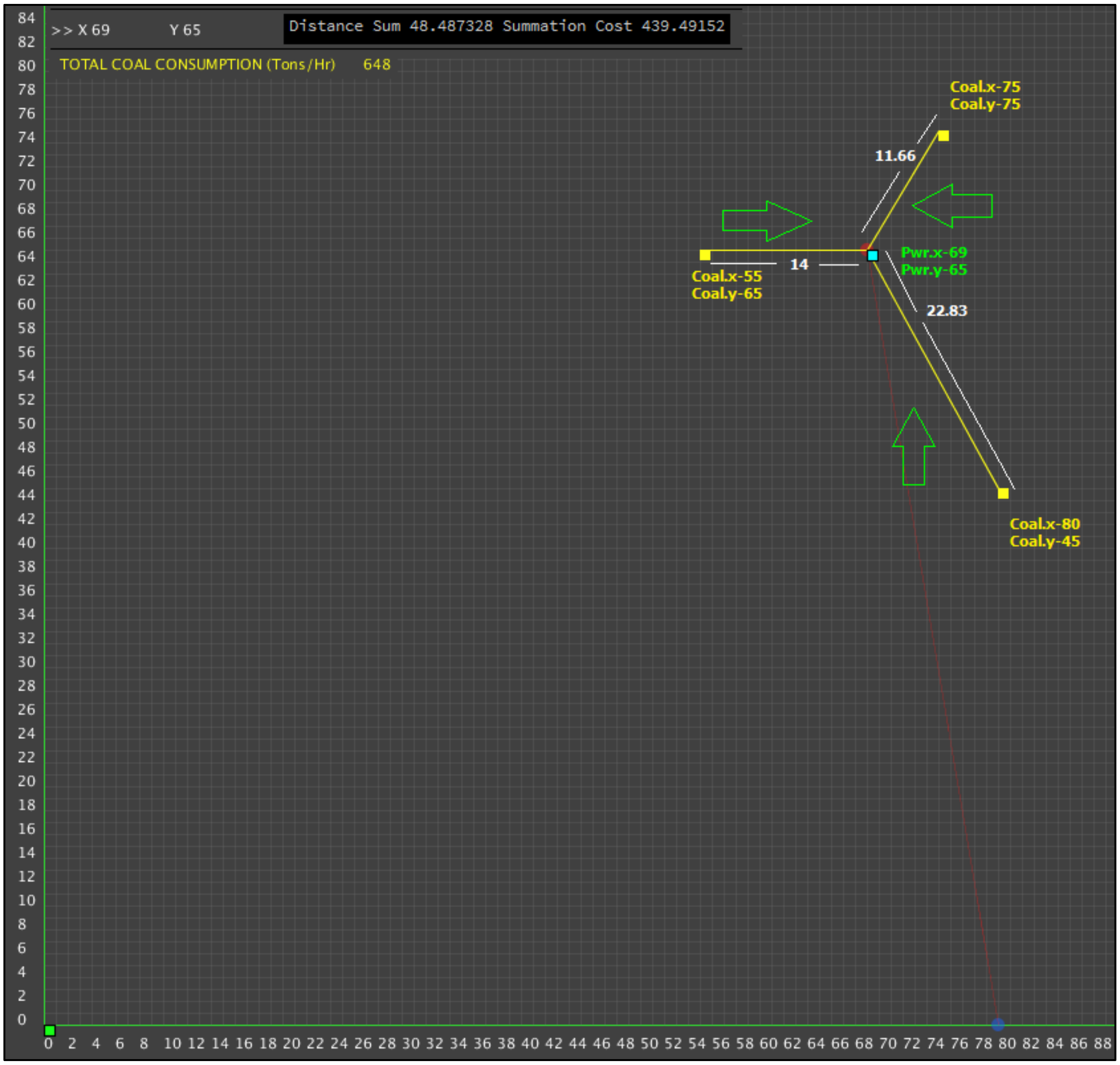


Figure 45. Coal transportation cost validation (Final State)

Simulation Graphics Output

The simulation is written in Processing software. Upon initialization, a display window appears, as shown in Figure 46. The new Power Plant (2), is placed on the grid (x_0, y_0). The resolution factor selected for the Gaussian plume dispersion model is two receptor points per kilometer. Circles represent the cities (customers), a green line represents the minimum spanning tree to connect all customers with the Power Plant (2). Yellow squares represent coal mines.

The program has evaluated all 10,000 points for an optimal solution. The best location to place Power plant (2) is (x_{59}, y_{64})[9] as shown in Figure 47. The total electric losses and transportation cost associated with (x_{59}, y_{64}) is $1,859.68, compared to $3050.64 observed at the start of simulation.

This marks the conclusion of the data analysis and results portion of the thesis project. The next chapter presents conclusion and recommendations of the thesis project.

[9] Blue square. The 'green' square is an exclusive location for minimum electric transmission, while 'yellow' square is exclusive for minimum coal delivery cost.

Initial State

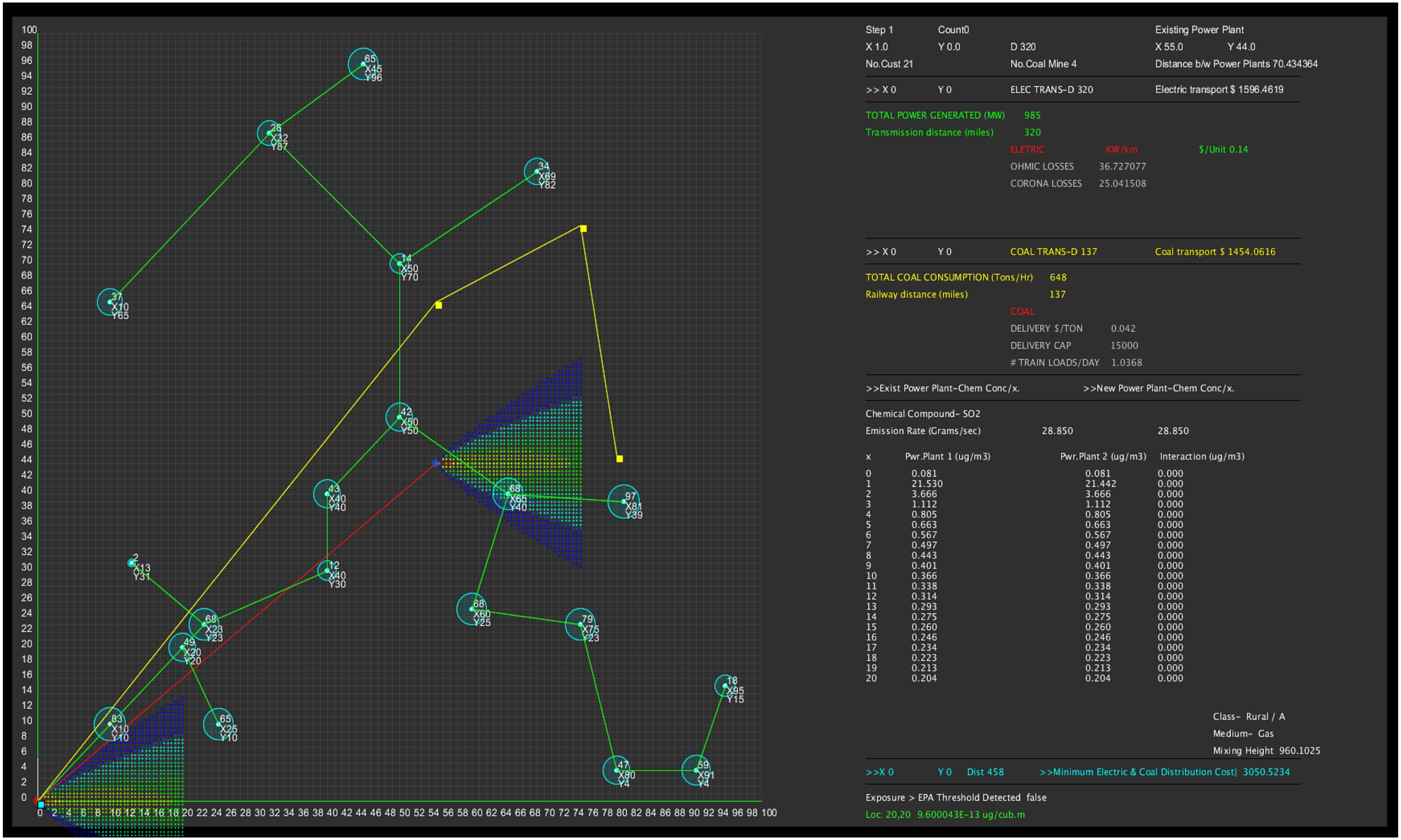


Figure 46. Display window of simulation upon initialization

Final State

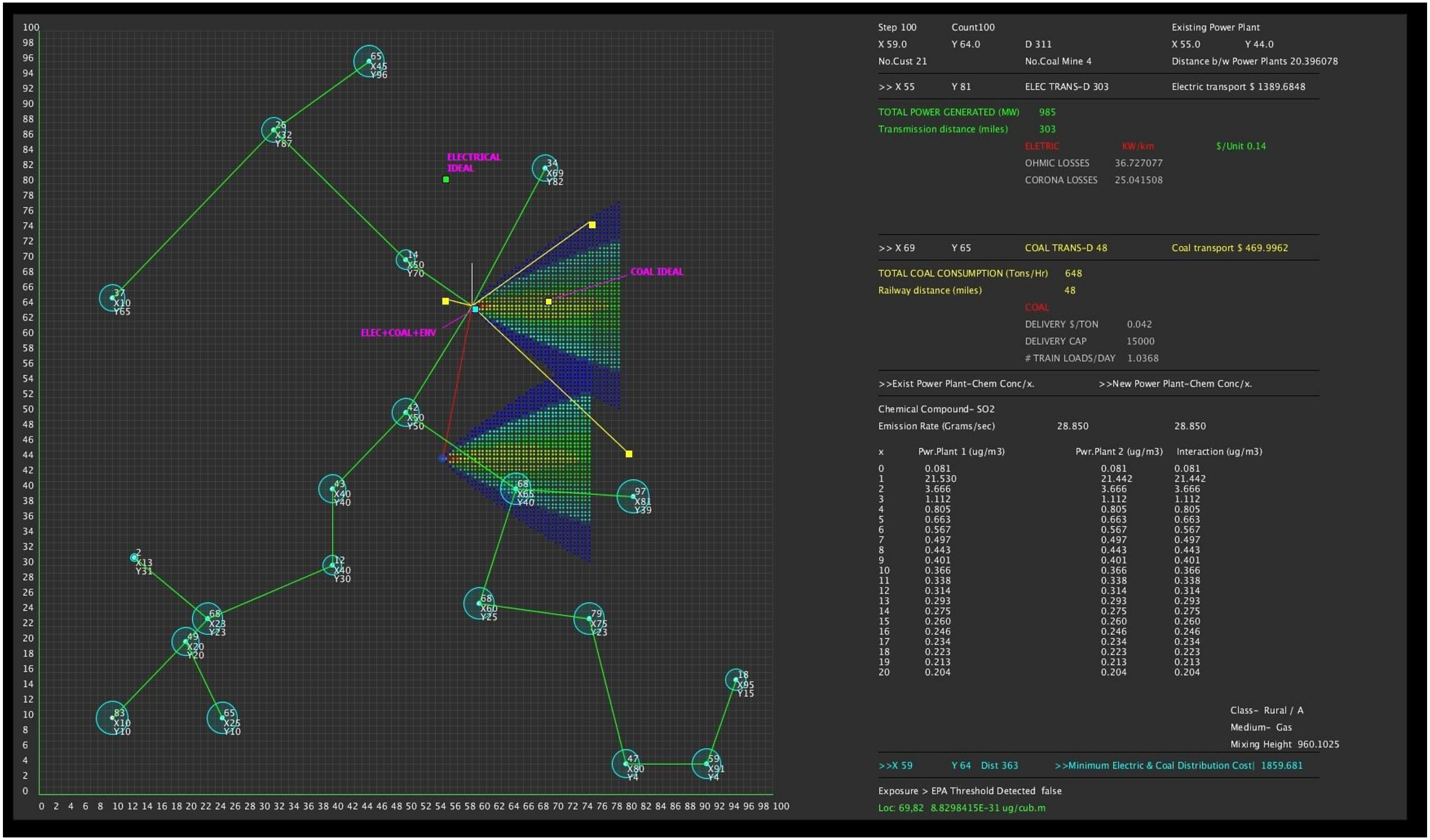


Figure 47. Display window of simulation upon finalization

Chapter 5. Conclusion and Recommendations

Conclusion

Coal-based electric power currently holds the largest share in electricity generated from non-renewable resources. Near term projections indicate that coal-based power will stay the primary source of electricity in developing nations. Coal-based power emissions are linked to operational efficiency of the power plant, boiler temperature, chemical content of coal, and filtering technologies of the power plant. The physical composition of these emissions can vary from solid (Particle Matter $_{(2.5)}$, Particle Matter $_{(10)}$, ash) and liquid (mercury, sulfuric acid) to gaseous states (SO_2, NO_x, VOC). The major concern regarding the wide-spread use of coal power, is the cofounded risk of these emissions being a detrimental health risk to the public. In any type of chemical exposure, the severity of the health risk is directly tied to chemical concentration and exposure time span. Some 'active' ways to reduce exposure of emissions to the public is by burning clean coal, operating the boiler at a higher temperature, and employing higher efficiency dry and wet scrubbers, while 'passive' ways to reduce exposure is by building a taller stack.

Coal power plants require a huge sum of capital investment and operational costs. The biggest operational cost for a coal power plant is the coal and the cost of coal delivery to the power plant. Another addition to this complex equation is factoring the transmission losses a power plant faces due to the sum of distance between the power plant and the respective customers. In terms of location analysis, we are faced with the following problem:

Given a grid of dimension $X_{(n)}$, $Y_{(n)}$, what location $_{(x, y)}$ can provide us with minimum cost of electric transmission losses and coal delivery, while ensuring that public exposure to coal-based emissions stay below EPA thresholds.

In this study we have successfully built a dynamic program, which simulates:

1. Coal power plant emission's dispersion, using a Gaussian Dispersion Model. The program has the capability to detect emission interaction between emissions of two coal power plants. The program can automatically block placement of a coal power plant near a city (customer), if the emission exposure to that customer is greater than a given EPA threshold.
2. A minimum spanning tree for electric transmission from a coal power plant to a given set of customers using Prim's algorithm. Transmission losses are influenced by distance between two points as well as the electric load on that transmission line. To deal with non-linear electric load between a power plant and various customers a regressive load transfer strategy is implemented. Combined use of Prim's algorithm and regressive load transfer strategy ensures a better location selection compared to other location analysis methodologies such as center of gravity, load factor rating, and load distance techniques.
3. A minimum spanning tree for coal delivery between a given set of coal mines and a power plant.

The program uses an exhaustive search strategy to find the best possible location for a new power plant. At each point on a 2D grid, the program first checks for emission interaction with another coal power plant and any respective customer. If the interaction exists with another coal power plant emission, the program combines the value of both emissions for that grid point. If the interaction exists with a client, the program compares the respective emission concentration[10] against the National Ambient Air Quality Standards (NIOSH) threshold value and uses a Boolean variable to store true/false value for further processing.

The program then runs a Prim's algorithm between the coal power plant and the customers to find the shortest tree to connect all customers to the power plant with transmission lines. A regressive load transfer strategy is used with Resistive and Corona Losses formulation to calculate the transmission losses. The transmission losses value is transformed into dollar value and stored using a float variable. Prim's algorithm is then applied to calculate a minimum spanning tree to connect coal mines to the power plant. The coal delivery cost is calculated by multiplying the coal load in tonnage with delivery charge of moving one ton of coal, one kilometer. The combined cost of electric transmission losses and coal delivery are compared to the current stored minimum cost value. If the new value of cost is less than the current stored value, and the emission exposure Boolean state is 'False', then the current value gets replaced by the new value, as well as the location coordinates. The program has the capability to deal with up to 30 cities with exclusive coordinates as well as 10 coal mines for location analysis. The embedded Gaussian Dispersion Model can successfully simulate the plume dispersion model up to a range of 25 km from the point source, with a resolution of five receptor points[11] per kilometer.

There are answers to the research questions posed in the beginning of this paper:

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[10] Both from individual or combined emission

[11] The processing time required to complete testing of 10,000 potential location is in days

Research Question 1

Which plume dispersion model can be combined with the location optimization algorithm in the proposed dynamic program that results in an optimal plant location, where NAAQS pollutant criteria and operational cost criteria are met?

Environmental protection agency proposed screening model	> Screen3
Environmental protection agency comprehensive model	> ISC3
Japanese Ministry of Economy, Trade, and Industry	> METI-LIS

Plume dispersion formulation from all of the above models has been successfully combined with a location optimization algorithm. However, during the validation process the residual between the programmed predicted results and METI-LIS were slightly higher in terms of [distance to maximum pollutant concentration] or [concentration along the wind direction]. An explanation is presented in the validation discussion on the next pages.

Research Question 2

Does the developed dynamic program assure a better location for a coal power plant where the cost of coal logistics as well as electric transmission is less, compared to a random pick or a greedy decision?

The developed dynamic program uses Prim's algorithm to produce transmission and coal logistics network. The Prim's algorithm network with application of regressive load transfer strategy provides less cost on both networks compared to other traditional location analysis strategies like center of gravity and load distance technique, etc.

Since the program uses an exhaustive search strategy, it looks at all possible locations on a grid map. It is certain to find a better location compared to a random search or a greedy decision.

Research Question 3

Does the power plant emission foot print for the determined location keeps the pollution factor less than the NAAQS threshold for 95% of the location population?

The program is built to sense plume concentration at ground level for a given customer during the search process. The user can select the threshold limit for a certain pollutant, and if the ground level concentration is greater than that threshold for the given power plant location on map, that position is eliminated for candidacy. However, there is an uncertainty factor which rises when the Gaussian Model is used to predict plume concentration plume beyond 30-50 km downwind range. The model cannot guarantee that beyond 25 km any customer present in the plume line will be exposed to pollutant concentration less than the National Ambient Air Quality Standards (NAAQS) threshold.

For validation, the Gaussian plume dispersion results for atmospheric conditions A-F were tested against the EPA Screen3 model, as well as Japanese METI-LIS model. Deviation in simulation plume dispersion results were within 25% of the EPA Screen3 model, but for METI-LIS model these deviations were much greater depending upon atmospheric condition. The significant differences from the METI-LIS model however do not compromise validity of our simulation since in simulation, the effective plume height of the plume is being calculated using the ‘Briggs’ Equations while the METI-LIS model uses ‘Concawe’ equations. The Briggs equation does not take into consideration isobaric specific heat and density of gas.

Simulation Prim’s algorithm results are verified by using R-Statistics ‘Optrees’ package. The results were found to be an exact match, concluding that the coding of Prim’s algorithm in the simulation program is correct.

The current program has successfully combined key ideas from the disciplines of environmental sciences, graph theory, electric engineering, operations management, and operations analysis to provide a multifunction platform that can be used by decision makers in the field of industrial planning, power generation, and permitting.

Recommendations

The current methodology offers a great room for future improvements. Currently, the equations used for plume modeling are from the EPA ISC3 Model. However, it would be more appropriate to use EPA 'AEROMOD' or 'CALPUFF' models. AEROMOD and CALPUFF provide more robust ways of calculating the planetary boundary layer, contain terrain and meteorological data pre-processing capability, able to simulate dispersion over vast distances and are recommended models by EPA for pollutant dispersion modeling. The current methodology operates in 2-dimensional grid however, to better accommodate various geographical features, a 3-dimensional grid should be built which allows formation of 'valleys' and 'peaks'.

In terms of losses, the current methodology only focuses on 'resistive' and 'corona' losses as part of the total transmission losses. However, 'Dielectric' losses can be also included in future research. In terms of financial feasibility, the grid search can relate to a 'Net Present Value' (NPV) equation. Each location on the map can have an associated NPV value. In the current methodology, the customer locations are considered 'static' with still demand throughout the simulation run. However, to better account for changes like rapid 'urbanization' or 'loss in population', demand structure can be made 'dynamic'.

The current methodology uses Prim's algorithm for producing minimum spanning tree between cities and a power plant. However, the total transmission distance can be further minimized by using the 'Steiner Tree'. The current coding of the simulation can be further improved, to decrease the total processing time as well as the aesthetics of program usage. For example, currently, each coal power plant in the simulation must be designed individually. However, it would be more appropriate to design coal power plants as 'class of objects' which would allow simulation of plume interaction greater than two emission sources.

Appendix

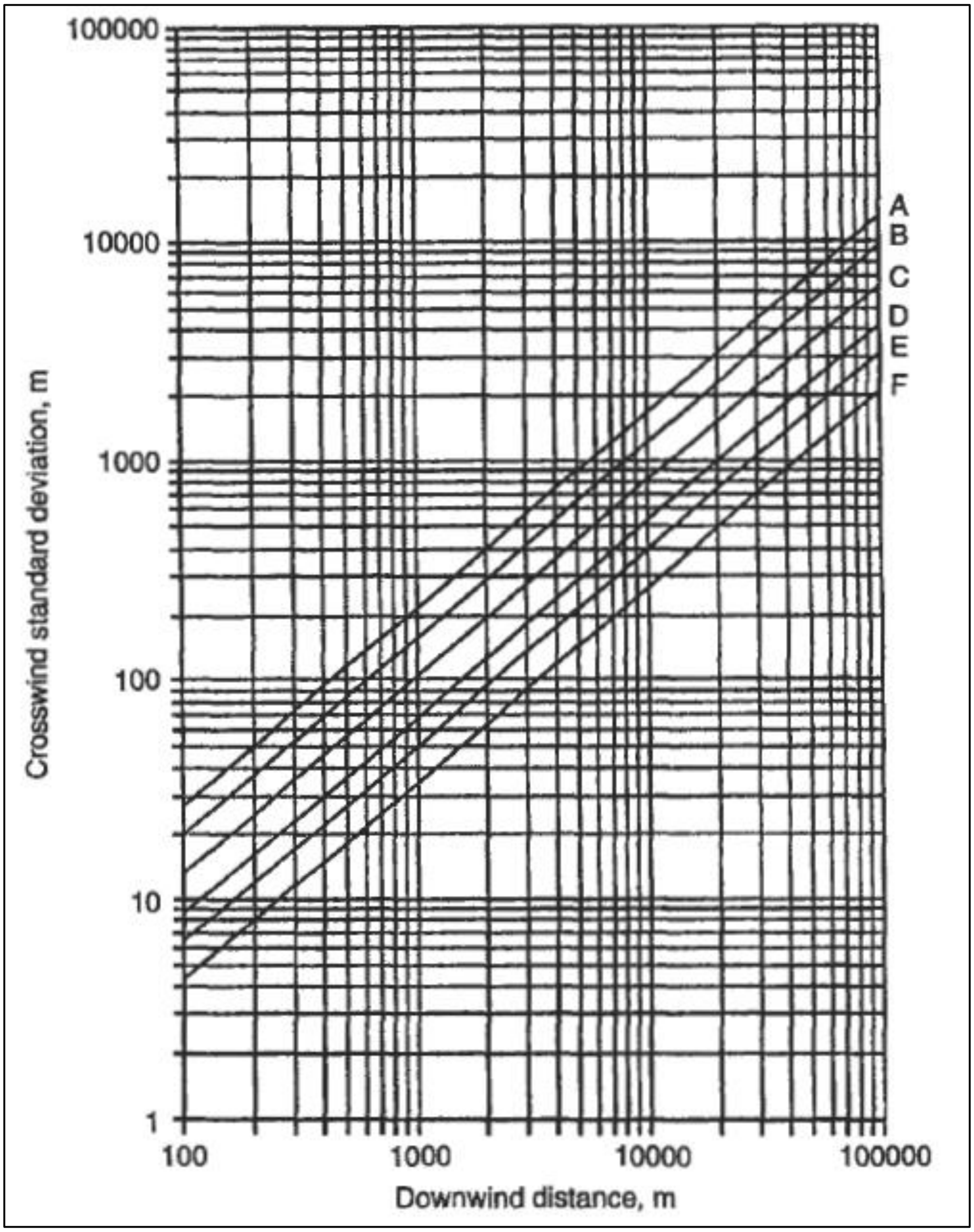

Figure A1. Horizontal crosswind dispersion (standard deviation), σy, as function of downwind range *(Weiner & Matthews, 2003)*

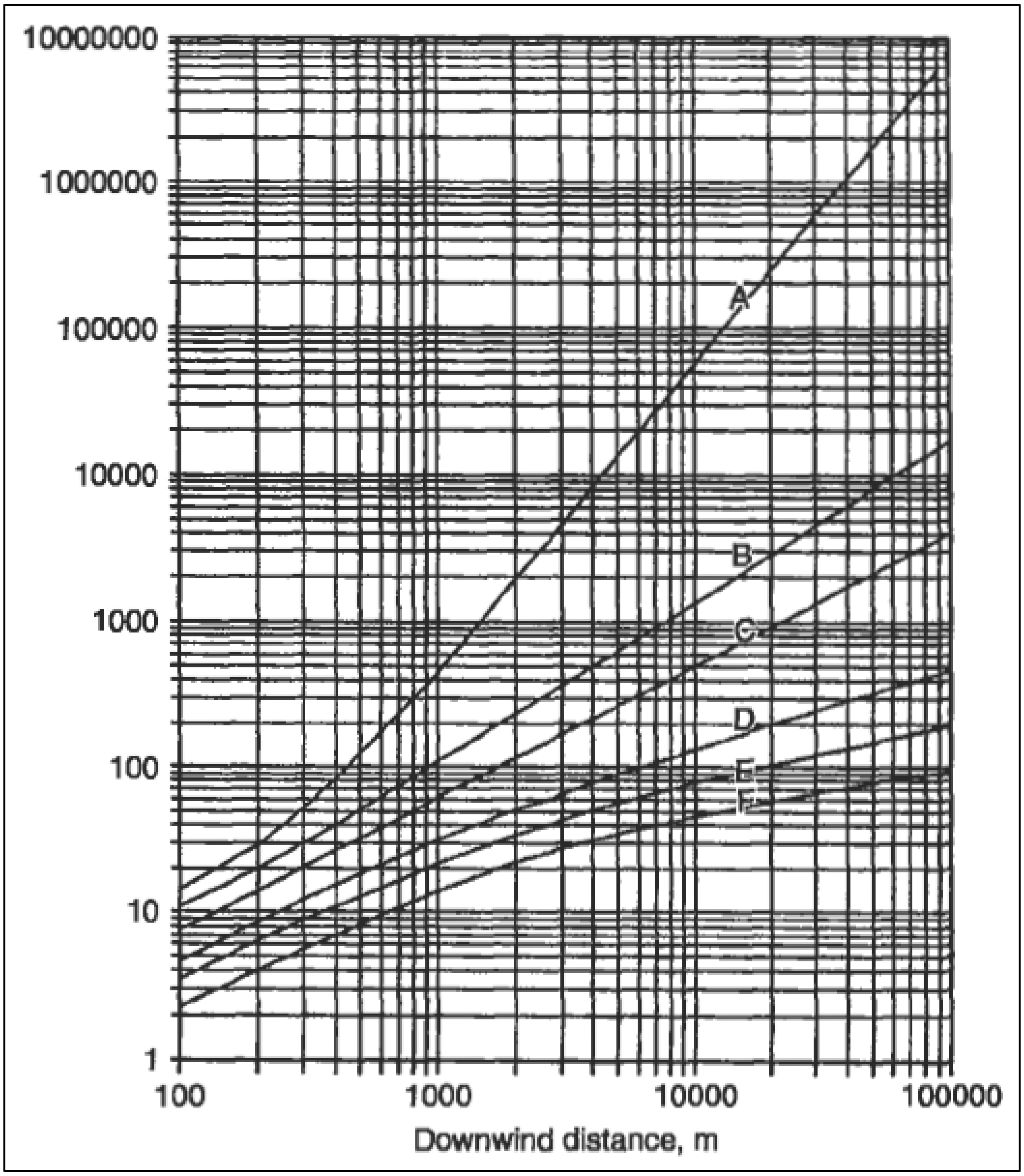

Figure A2. Vertical dispersion (standard deviation) σ_z, as function of downwind range *(Weiner & Matthews, 2003)*

Disclaimer

References

AERMOD: Description of model formulation (pp. 1-91, Tech. No. EPA-454/R-03-004). (2004). Durham, NC: U.S. Environmental Protection Agency.

Ahuja, R. K., Magnanti, T. L., & Orlin, J. B. (1993). *Network flows: Theory, algorithms, and applications*. New Jersey: Prentice Hall.

Alemayehu, D., & Hackett, F. (2015). Gaussian dispersion model to estimate the dispersion of particulate matters (Pm2.5) and sulfur dioxide (So2) Concentrations on Tribal Land, Oklahoma. *American Journal of Environmental Sciences,11*(6), 440-449. doi:10.3844/ajessp.2015.440.449

Alonso, F., & Greenwell, C. A. (2013, February 1). Underground vs. overhead: Power line installation-cost comparison and mitigation. *Electric Light & Power*. Retrieved from https://www.elp.com/index.html

Ambiente, M. (2010). Pollutant Release and Transfer Register. Retrieved April 26, 2018, from http://www.mma.gob.cl/retc_ingles/1316/w3-article-51518.html

E., & E. (1996, October). Anthracite coal combustion final section. Retrieved April 26, 2018, from https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s02.pdf

Aul, E., & Pechan, E. (1996). *External combustion sources-anthracite coal combustion final section* (pp. 1-13, Rep.). Durham, NC: Environmental Protection Agency.

Awasthi, S., Khare, M., & Gargava, P. (2006). General plume dispersion model (GPDM) for point source emission. *Environmental Modeling & Assessment,11*(3), 267-276. doi:10.1007/s10666-006-9041-y

Ballou, R. H. (2004). *Business logistics management: Planning, organizing, and controlling the supply chain*. Upper Saddle River, N.J.: Prentice-Hall.

Bhatti, S. S., & Haq, S. U. (2015). Electric power transmission and distribution losses overview and minimization in Pakistan. *International Journal of Scientific & Engineering Research,6*(4), 1108-1112. doi:ISSN 2229-5518

Bond, S., Sims, S., & Dent, P. (2013). *Towers, Turbines and Transmission Lines: Impacts on Property Value*. John Wiley & Sons.

Brigden, K., & Santillo, D. (2002). *Hazardous emissions from Philippine coal-fired power plants* (pp. 1-21, Rep.). Exeter: Green Peace. http://www.greenpeace.org

Britannica, T. E. (2017, April 27). Computer simulation. *Encyclopedia Britannica.* Retrieved April 26, 2018, from https://www.britannica.com/technology/computer-simulation

Union of Concerned Scientists. (2017, December 19). Coal and air pollution. *Union of Concerned Scientists*. Retrieved April 26, 2018, from https://www.ucsusa.org/clean-energy/coal-and-other-fossil-fuels/coal-air-pollution#.WuHylfkvzIV

Department of the Environment and Heritage. (2005). Nitrogen dioxide (NO2). *Department of the Environment and Heritage*. Retrieved April 26, 2018, from http://www.environment.gov.au/protection/publications/factsheet-nitrogen-dioxide-no2

EIA. (2017, August 31). Coal mining and transportation. *U.S. Energy Information Administration - EIA - Independent Statistics and Analysis.* Retrieved from https://www.eia.gov/energyexplained/index.cfm?page=coal_mining

EIA. (2017). *International energy outlook. 2017*(pp. 1-76, Rep. No. DOE/EIA-0484(2017)). U.S Energy Information Administration.

EIA. (2018, March 7). What is U.S. electricity generation by energy source? *U.S. Energy Information Administration - EIA - Independent Statistics and Analysis.* Retrieved April 26, 2018, from https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

Electrical Technology. (2018, February 26). Corona effect in transmission lines & power system. *Electrical Technology*. Retrieved April 26, 2018, from https://www.electricaltechnology.org/2018/02/corona-effect-discharge-transmission-lines-power-system.html

EPA. (1984). *Locating and estimating air emissions from sources of chromium* (pp. 1-235, Rep. No. EPA-450/4-84-007G). Durham, NC: U.S Environmental Protection Agency.

EPA. (1995). *User's guide for the Industrial Source Complex (ISC3) dispersion models.* (Vol. II, pp. 1-128, Rep. No. EPA-454/B-95-003b). Durham, NC: U.S. Environmental Protection Agency.

EPA. (1998). *NOx How nitrogen oxides affect the way we live and breathe* (pp. 1-6, Publication No. EPA-456/F-98-005). Durham, NC: Environmental Protection Agency.

EPA. (2016, December 20). NAAQS table. *United States Environmental Protection Agency*. Retrieved April 26, 2018, from https://www.epa.gov/criteria-air-pollutants/naaqs-table

EPA. (2016, September 27). Air quality models. *United States Environmental Protection Agency*. Retrieved April 26, 2018, from https://www.epa.gov/scram/air-quality-models

EPA. (2017, June 12). Mercury and air toxics standards. Cleaner power plants. *United States Environmental Protection Agency*. Retrieved April 26, 2018, from https://www.epa.gov/mats/cleaner-power-plants#limits

EPA. (2018, January 31). Health effects notebook for hazardous air pollutants. *United States Environmental Protection Agency*. Retrieved April 26, 2018, from https://www.epa.gov/haps/health-effects-notebook-hazardous-air-pollutants

Erickson, J. (2015). Minimum spanning trees. *Algorithms, Etc*. Retrieved April 26, 2018, from http://jeffe.cs.illinois.edu/teaching/algorithms/

Finkelman, R. B., Orem, W., Castranova, V., Tatu, C. A., Belkin, H. E., Zheng, B., . . . Bates, A. L. (2002). Health impacts of coal and coal use: Possible solutions. *International Journal of Coal Geology,50*(1-4), 425-443. doi:10.1016/s0166-5162(02)00125-8

Frontline Systems, Inc. (2012, April 26). Optimization Problem Types - Mixed-Integer and Constraint Programming. *Frontline Systems.* Retrieved April 26, 2018, from https://www.solver.com/integer-constraint- programming

Geiger, A., & Cooper, J. (2010). *Overview of airborne metals regulations, exposure limits, health effects, and contemporary research* (pp. 1-56, Rep.). Portland, OR: Environmental Protection Agency. https://www3.epa.gov/ttnemc01/prelim/otm31appC.pdf

Gourgue, H., Aharoune, A., & Ihlal, A. (2015). Dispersion of the NOx emissions from chimneys around industrial area: Case study of the company CIBEL II. *Materials Today: Proceedings*,*2*(9), 4689-4693. doi:10.1016/j.matpr.2015.09.024

Guttikunda, S. K., & Jawahar, P. (2014). Atmospheric emissions and pollution from the coal-fired thermal power plants in India. *Atmospheric Environment*,*92*, 449-460. doi:10.1016/j.atmosenv.2014.04.057

Harting, C. (2010, October 24). Curt Harting. *AC Transmission Line Losses.* Retrieved April 26, 2018, from http://large.stanford.edu/courses/2010/ph240/harting1/

Harvard Health Publishing. (2013, January). Carbon monoxide poisoning. *Harvard Health Publishing.* Retrieved April 26, 2018, from https://www.health.harvard.edu/diseases-and-conditions/carbon-monoxide-poisoning-

Heritage Protection. (2013, August 29). Inversions | Environment, land and water. *Queensland Government*. Retrieved April 26, 2018, from https://www.qld.gov.au/environment/pollution/monitoring/air-monitoring/meteorology-inversions

Hillier, F. S., & Lieberman, G. J. (2005). *Introduction to Operations Research*. Boston: McGraw-Hill Higher Education.

IEA Statistics. (2014). Electricity production from coal sources (% of total). *The World Bank.* Retrieved April 26, 2018, from https://data.worldbank.org/indicator/eg.elc.coal.zs

Liu, K. (2016). The major root causes of smog in China and technologies and solutions to reduce It. *Frontiers of Engineering Management,3*(4), 343. doi:10.15302/j-fem-2016053

Macdonald, R., Ph.D., P.Eng. (2003). *Theory and objectives of air dispersion modelling.* pp. 1-27). Waterloo, ON: University of Waterloo. Modelling Air Emissions for Compliance.

METI. (2005). *Ministry of Economy, Trade and Industry Low Rise Industrial Source Dispersion Model METI-LIS Model* (pp. 1-56, Tech.). Tokyo: Ministry of Economy, Trade and Industry of Japan.

Razi, K. M., & Hiroshi, M. (2012). Modeling of atmospheric dispersion of mercury from coal–fired power plants in Japan. *Atmospheric Pollution Research,3*(2), 226-237. doi:10.5094/apr.2012.025

Revelle, C., & Eiselt, H. (2005). Location analysis: A synthesis and survey. *European Journal of Operational Research,165*(1), 1-19. doi:10.1016/j.ejor.2003.11.032

Airgas. (2018, February 14). Safety data sheet-Nitrogen dioxide. *Airgas*. Retrieved April 26, 2018, from https://www.airgas.com/msds/001041.pdf

Shiffman, D. (Producer). (2016, March 18). 9.9: Minimum Spanning Tree (Prim's Algorithm) - p5.js Tutorial. *YouTube.* Retrieved April 26, 2018, from https://www.youtube.com/watch?v=BxabnKrOjT0

Skiena, S. S. (2008). *The Algorithm Design Manual* (2nd ed.). London: Springer.

Study Electrical. (2017). Corona Effect in Power System. *Study Electrical.* Retrieved April 26, 2018, from http://www.studyelectrical.com/2015/12/corona-effect-in-power-system-transmission-lines.html

Tonmitr, K., Ratanabuntha, T., Tonmitr, N., & Kaneko, E. (2016). Reduction of power loss from corona phenomena in high voltage transmission line 115 and 230 kV. *Procedia Computer Science,86*, 381-384. doi:10.1016/j.procs.2016.05.108

Tran, H. N., & Mölders, N. (2012). Numerical investigations on the contribution of point source emissions to the PM2.5 concentrations in Fairbanks, Alaska. *Atmospheric Pollution Research,3*(2), 199-210. doi:10.5094/apr.2012.022

Turner, D. (1970). *Workbook of atmospheric dispersion estimates* (pp. 1-92, Rep.). U.S Environmental Protection Agency.7th printing January 1974 Office of Air Programs Publication No. AP-26

U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (2012, November 16). Retrieved April 26, 2018, from https://www.eia.gov/coal/transportationrates/archive/2010/index.php

U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (2016, February 24). Retrieved April 26, 2018, from https://www.eia.gov/todayinenergy/detail.php?id=25092

U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. (2018, April 6). Retrieved April 26, 2018, from https://www.eia.gov/tools/faqs/faq.php?id=667&t=6

Universal Industrial Gases, Inc. (2015, April 25). Material safety data sheet: Gaseous CO_2. *Universal Industrial Gases, Inc.* Retrieved April 26, 2018, from http://www.uigi.com/MSDS_gaseous_CO2.html

Varma, S., Srimurali, M., & Varma, S. (2014). Prediction of ground level concentrations of air pollutants using gaussian model, Rayalaseema thermal power project, Kadapa, A.P., India. *Energy and Environmental Engineering,*91-97. DOI:10.13189/eee.2014.020402

Weiner, R. F., & Matthews, R. A. (2003). *Environmental Engineering* (4th ed.). Burlington, MA: Elsevier Science (USA). ISBN: 0750672943

Weisstein, E. (2018, April 20). Complete Graph. *Wolfram Alpha.* Retrieved April 26, 2018, from http://mathworld.wolfram.com/CompleteGraph.html

Xi e, L., Huang, Y., & Qin, P. (2016). *Spatial distribution of coal fired power plants in China* (pp. 1-30). Peking: Environment for Development. EfD DP 16-25