DEVELOPMENT OF AIR POLLUTANTS DISPERSION ALGORITHM IN URBAN INDUSTRIAL PARK FOR AIR POLLUTION SIMULATION

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

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OCTOBER 2019

DEDICATION

This thesis is dedicated to Umi and Abi, Mak and Ayah, and all my family members who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my beloved wife and children, Nur Amira, Maryam Hannah, Muhammad Yusuf Faris who taught me that even the largest task can be accomplished if it is done one step at a time.

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Dr. Muhamad Hasbullah Padzillah, for encouragement, guidance, critics and friendship. I am also thankful to my co-supervisor Associate Professor Dr. Kahar Osman for his thorough guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Universiti Teknologi Malaysia (UTM), Majlis Amanah Rakyat (MARA) and Kementerian Pendidikan Tinggi (KPT) for funding my Ph.D study. Assoc. Prof. Takahisa Yamamoto from Gifu National College of Technology, Japan also deserve special thanks for his assistance in numerical and turbulence implementations.

My fellow Computational Fluid Mechanics (CFM) laboratory members should also be recognised for their support especially to Hazmil, Zamani, Ikhwan, Hakim, Rashidi and others. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space.

I am truly grateful to all my family members. A very special thanks to my lovely and beloved wife, Nur Amira for continuous support and countless sacrifices through hardship in all these years. This thesis would not have been completed without her being on my side.

ABSTRACT

Environmental Impact Assessment analysis is generally restricted to neighbourhood scale air pollution simulation using the Gaussian Plume model (GPM). This approach expected to enhance the resolution of ground level concentration in the conventional GPM based software up to building scale by using Computational Fluid Dynamics (CFD) model alongside the GPM. The aim of this study was to develop an air pollution prediction algorithm for air pollutants release from industrial stacks. It was used to estimate, simulate and control air pollution in urban industrial park using integrated GPM and CFD model. The GPM was used for regional air pollutant level prediction to find high pollutant concentration zones. Whereas, CFD model was used for detailed simulation on respective polluted areas. In order to achieve this, a building detection algorithm from satellite image based on building footprint detection and height estimation from shadow thickness has been proposed to reduce pre-processing effort of the present CFD solver. The present CFD algorithm were based on Fractional Step Method for efficient steady state solver and Prandtl Mixing Length turbulence model for low cost turbulence calculation. The accuracy of the CFD algorithm has been tested and verified against benchmark problems (less than 3% error for lid-driven cavity problem, less than 8% for flow over isolated cube). It was discovered that CFD algorithm developed in this study is sufficiently accurate as other wind flow models with slight over prediction in wind speed by 1.04 m/s (15.6% are below 10% error) and able to predict the wind direction correctly within 60° angle (37.5% are within 15° angle) compared to measurement data. Air pollutant release from major stacks in Pasir Gudang Industrial Park was studied using GPM and high NO_2 concentration zone (1800 µg/m^3) was found in Taman Air Biru. Results suggest that 24-hour averaged SO_2 and PM_{10} maximum ground level concentration are well within Ambient Air Quality Standard (AAQS) limits with 8.9 µg/m^3 (8.4%) and 11.4 µg/m^3 (7.6%) respectively. Meanwhile, 24-hour averaged NO_2 concentration exceed AAQS limit with 270.3 µg/m^3 (360%). The detailed CFD simulation of wind distribution and pollutant dispersion process within the area was presented. Present CFD model (1800 µg/m^3) over predicted 1-hour averaged NO_2 ground concentrations by a factor of 3 compared to the present GPM (700 µg/m^3) but it provides more information on wind distribution as well as pollutant dispersion process. A new atmospheric dispersion solver has been developed that is able to simulate pollutant dispersion on both regional scale using GPM and building scale using CFD model.

ABSTRAK

Analisis Penilaian Kesan Alam Sekitar umumnya terhad kepada skala kejiranan bagi simulasi bahan pencemar udara menggunakan model Gaussian Plume (GPM). Kaedah ini menambahbaik resolusi simulasi kepekatan bahan pencemar atas tanah dalam perisian konvensional GPM kepada skala bangunan dengan menggabungkannya bersama model Dinamik Bendalir Berkomputer (CFD). Kajian ini bertujuan untuk membangunkan algoritma ramalan pencemaran udara bagi pelepasan bahan pencemar daripada cerobong asap industri. Ia digunakan untuk meramal, mensimulasi dan mengawal pencemaran udara di kawasan perindustrian bandar dengan menggunakan GPM dan model CFD yang disatukan dalam satu algoritma. GPM digunakan untuk meramal tahap pencemaran udara secara kasar bagi mencari kawasan berkepekatan tinggi. Model CFD pula digunakan untuk simulasi terperinci di kawasan berkepekatan tinggi tersebut. Algoritma pengesanan bangunan dari imej satelit menggunakan teknik pengesanan tapak bangunan dan anggaran ketinggian bangunan berdasarkan ketebalan bayang telah dibangunkan untuk meringkaskan pra-pemprosesan model CFD. Dalam tesis ini, algoritma CFD menggunakan kaedah *fractional step* untuk penyelesaian secara efisien dan model pergolakan *Prandtl Mixing Length* untuk pengiraan yang pantas. Ketepatan algoritma ini telah diuji dan disahkan menggunakan data eksperimen piawai dan kajian eksperimen secara berperingkat (kurang 3% untuk kaviti, kurang 8% untuk pergerakan udara merentasi kiub). Hasil kajian menunjukkan algoritma CFD yang dibangunkan adalah cukup tepat kerana model pergerakan angin meramal sebanyak 1.04 m/s (15.6% mempunyai sisihan kurang 10%) lebih tinggi daripada dapatan eksperimen dan dapat meramalkan arah angin dengan betul dalam lingkungan sudut 60° (37.5% mempunyai sisihan kurang 15°) berbanding dengan data piawai. Pencemaran udara dari cerobong asap utama di Taman Perindustrian Pasir Gudang telah dikaji menggunakan GPM dan zon kepekatan NO_2 yang tinggi terdapat di Taman Air Biru. Keputusan mencadangkan bahawa kepekatan purata 24-jam SO_2 dan PM_{10} adalah di bawah had kualiti udara (AAQS) iaitu sebanyak 8.9 $\mu g/m^3$ (8.4%) dan 11.4 $\mu g/m^3$ (7.6%). Sementara itu, kepekatan purata 24-jam NO_2 melebihi had AAQS sebanyak 270.3 $\mu g/m^3$ (360%). Simulasi CFD yang terperinci terhadap pergerakan angin dan proses penyebaran pencemar di kawasan ini telah dibentangkan. Model CFD dalam kajian ini (1800 $\mu g/m^3$) terlebih anggar kepekatan purata 1-jam NO_2 dengan faktor 3 berbanding GPM (700 $\mu g/m^3$) tetapi ia mempunyai data yang lebih lengkap mengenai taburan angin dan juga proses pergerakan bahan pencemar udara. Algoritma penyebaran bahan pencemar udara yang baru telah dibangunkan bagi mensimulasikan penyebaran bahan pencemar udara pada kedua-dua skala serantau menggunakan GPM dan skala bangunan menggunakan model CFD.

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LIST OF ABBREVIATIONS

AAQG	-	Ambient Air Quality Guidelines
AAQS	-	Ambient Air Quality Standard
ADMS	-	Atmospheric Dispersion Modelling System
AECOPD	-	Acute Exacerbations Of Chronic Obstructive Pulmonary Disease
AGREE	-	Accidental Gas Release
AMR	-	AMR Environmental Pte. Ltd.
AMS	-	American Meteorological Society
CALINE	-	California Line Source Model
CALPUFF	-	California Puff Modelling System
CFD	-	Computational Fluid Dynamics
CTDMPLUS	-	Complex Terrain Dispersion Model
GIS	-	Geo Information System
GLC	-	Ground-Level Concentration
IAQ	-	Indoor Air Quality
IOP	-	Intensive Observational Periods
IMMDADS	-	Integrated Malaysian Meteorological Data Atmospheric Dispersion Software
ISC	-	Industrial Source Complex
JU2003	-	Joint Urban 2003 Field Measurement
EIA	-	Environmental Impact Assessment
EPA	-	Environmental Protection Agency
ESRI	-	Environmental Systems Research
GPU	-	Graphics Processing Unit
KAMI	-	Kualiti Alam Modularized Incinerator
LES	-	Large Eddy Simulation
LIDAR	-	Light Detection and Ranging
LPG	-	Liquefied Petroleum Gas
NAME	-	Numerical Atmospheric-dispersion Modelling Environment
NOx	-	Oxides of Nitrogen

O_3	-	Ozone
PM_{10}	-	Particulate Matter 10 Micrometer in Size
$PM_{2.5}$	-	Particulate Matter 2.5 Micrometer in Size
RAM	-	Random Access Memory
RANS	-	Reynolds Averaged Navier-Stokes
RGB	-	Red Green Blue
RMG	-	Recommended Malaysian Guidelines
SAR	-	Synthetic-Aperture Radar
SF_6	-	Sulfur Hexaflouride
SRTM	-	Shuttle Radar Topography Mission
TDMA	-	Tri-Diagonal Matrix Algorithm

LIST OF SYMBOLS

β	-	Artificial Compressibility
C	-	Pollutant Concentration
D	-	Molecular Diffusivity
H	-	Height of Cube
h_e	-	Effective Stack Height
h_s	-	Stack Height
h'_s	-	Effective Stack Height
k	-	Karman Constant
K_c	-	Turbulent Diffusivities of Scalar Variables
l_{mix}	-	Mixing Length
μ	-	Kinematic Viscosity
n	-	Normal to Boundary
ρ	-	Fluid/Air Density
p	-	Power Law Exponents
P	-	Deviation of Pressure
Q	-	Stack Volumetric Flow Rate
S_c	-	Source/Sink Term of Pollutants
SF_6	-	Sulphur Hexafluoride
T_a	-	Ambient Air Temperature
T_s	-	Stack Gas Temperature
t	-	Time
τ_{ij}	-	Reynolds Stress Tensor
τ	-	Artificial Time
u	-	Wind Velocity
U_c	-	Velocity Independent of Outlet Plane
U_i	-	ith Mean Velocity Component
u_s	-	Wind Velocity at Stack Height
U_t	-	Friction Velocity
U, V, W	-	Velocity in X, Y and Z Directions

CHAPTER 1

INTRODUCTION

1.1 Research Background

Air pollutant release from transportation and industries have been major threat to human health and wellness in rural and urban areas (Tian *et al.*, 2019). Air pollutants are the early origin of respiratory diseases (Kim *et al.*, 2018) that need to be constantly monitored to preserve air quality and environment. One of the methods to control air pollution is by regulating law to limit permissible amount of harmful gases into the atmosphere. In order to do so, air pollution dispersion simulation is needed to estimate the allowable release amount and assess the impact of unhealthy chemical releases to the surrounding ambient atmosphere.

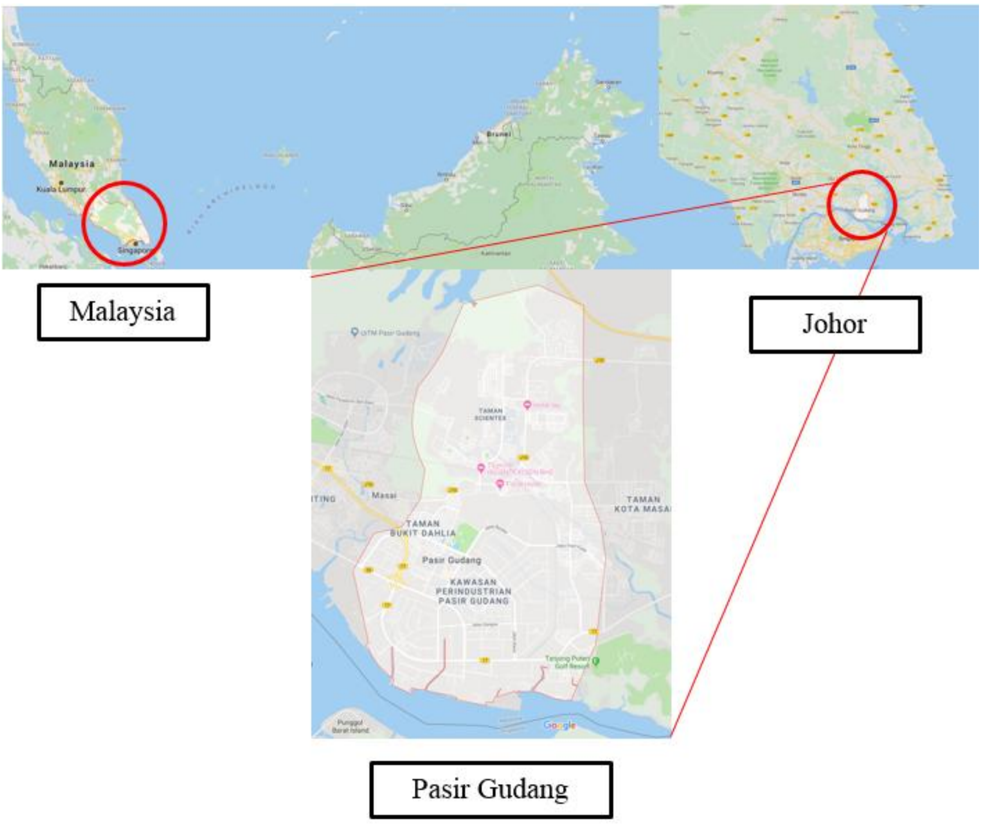
In environmental town planning, air pollutant prediction and simulation in urban industrial park is important to identify critical areas where pollutant entrapments are taken place due to vehicle emissions, industrial release, agricultural waste and construction dusts. They are used by urban planners for long-term air pollution risk and health assessments, evacuation plan during accidents and assists in smart city design with good ventilation resulting in effective natural pollutant removal process. Besides, the analysis prevents failed urban design such as developing residential areas around polluted areas as well as evade late warnings of severe pollution levels that adversely affect health of citizen in the long run. In addition, detailed simulation can also be used to locate strategic station for air cleaning devices in urban areas.

In practical use, air pollutants dispersion software are developed based on Gaussian Plume model. They are based on conical plume assumption in which the concentration across the plume cross-section has a Gaussian (normal) distribution. Those software are used to estimate the pollutant concentration on the ground around industrial stack such as the well-known U.S. Environmental Protection Agency (EPA)

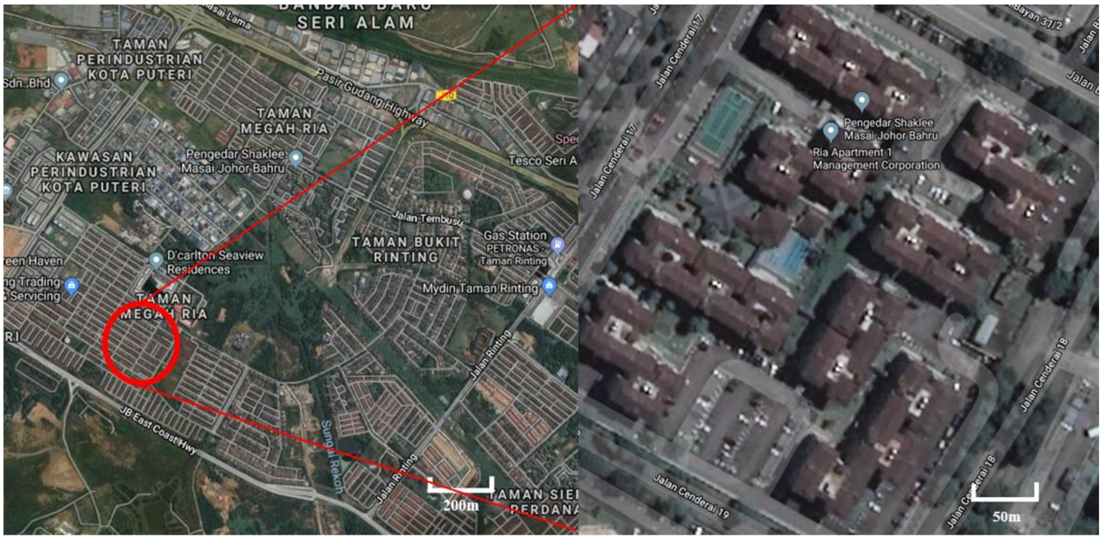
Regulatory Model (AERMOD). This model is widely used for Environmental Impact Assessment (EIA) because it is sufficiently accurate, relatively simple to run with short computing time and low computer requirement. On average computer, for 50 x 50 number of grids with 200m distance between each grid (10 km x 10 km simulation area), those software usually take seconds to calculate 1 hour ground-level pollutant concentration (GLC) and approximately 15 to 40 minutes to calculate 1 year GLC. The Random Access Memory (RAM) used is relatively low compared to other advanced models since Gaussian Plume model can be run effectively with lower than 5000 number of grid points. However, Gaussian Plume model falls short in complex built environment due to flat terrain assumptions that were used during model development.

For complex urban structures, Computational Fluid Dynamics (CFD) models are better in handling three-dimensional (3D) air flow and pollutant dispersion within building configurations but it is less popular among environmental modellers due to high computing load required, complexity of the setup and long simulation times (Antonioni *et al.*, 2012). In practice, CFD models are only able to conduct simulation on approximately 1 km x 1 km x 1 km computational domain with lower than 10 m in grid size (approximately 1 million grid points). Though, it may take more than 1 hour to complete the calculation for steady flow and up to days and months for unsteady and transient flow. Moreover, the simulation times might increase significantly for larger CFD mesh (discrete grid points to solve air/fluid equations). In common, such simulations can take more than 1 GB of RAM usage on average computer. For these reasons, CFD analysis are generally not included in EIA analysis. Although air pollutant prediction and simulation has been studied extensively, no attempt has been made to analyse detailed wind distribution and pollutant dispersion process on high concentration zones in urban industrial park (network of stacks with nearby residential areas) predicted from conventional Gaussian Plume model.

In this study, both models are developed together in a single algorithm to complement their limitations. Due to poles apart models' structure, fundamental equations, coding architectures and massive programming effort to integrate both models in a single algorithm, there is no effort found in the literature on integrating both models as one. The primary advantage acquired by integrating both models in the same algorithm is that it allows user to find the high concentration zones using Gaussian Plume model and further investigate pollutant dispersion process within the areas using CFD model. In this study, the code of both models are written from scratch to ensure unified programming structure in order to carry out the integration. The main difficulty of this study lies on figuring out coding implementation of collective governing equations and assuring accuracy, stability, efficiency and robustness of the algorithm. Integrated Gaussian and CFD model allow multiple scale air pollutant dispersion prediction commencing from regional/neighbourhood estimation of air pollution level using Gaussian Plume model in neighbourhood scale (10^4 m in computational domain size) up to detailed building scale simulation (10^3 m) using CFD model as shown in Figure 1.1 (residential area in Pasir Gudang) (Cui et al., 2016). Hence, ability of the present algorithm developed in this study ranging from conducting routine air pollution assessment for regional estimation of air pollution level to more detailed wind flow analysis within building structures in the urban industrial park.



(a)



(b) (c)

Figure 1. 1 (a) Location of Pasir Gudang Industrial Park (b) Neighbourhood scale (10^4 m or 10 km x10 km using Gaussian Plume model) (c) Building scale (10^3 m or 1 km x 1 km using CFD model) (Google Maps, 2019).

Applying CFD models on complex urban structures requires extra task to remodel the buildings. Although accuracy of CFD models are satisfactory in recent years, generating urban 3D building models for CFD solvers still require manual effort especially in highly populated areas with multiple building configurations. In commercial software such as the well-known ANSYS Fluent software, users need to manually model the buildings using third-party software such as SOLIDWORKS (Bock, 2015). In the present CFD model, a smart function to automatically generate CFD mesh consisting urban buildings using image processing of satellite image is developed. Even though modellers are able to obtain the building data from Geographic Information System (GIS) data centre, several limitations of GIS approach restrict the convenience of the process. Those constrains include digitizing accuracy, incomplete data for rural and remote areas, costly and time consuming to obtain the data, manual update that causes human error and require good understanding on software architecture to extract available information before data manipulation (Schmit *et al.*, 2006).

In contrast, this study proposes a more reliable and effective way to generate building geometries using satellite image for CFD simulation. This approach analyses building footprints information and estimates the height using shadow length to produce urban geometries by extruding the footprints detected beforehand. Furthermore, this technique only requires Red Green Blue (RGB) satellite image (.jpg, .jpeg, .png) to process which is much easier to obtained, low in cost, faster data acquisition, good availability, low memory requirement, efficient building generation process, partially automated and suitable for repetitive building extraction for entire city mapping application. From our observation, upcoming technological utilization that are predicted to be impacting environmental modelling study is CFD and automatic building generation from satellite image. This study attempts to merge unique capabilities of both research areas to produce a smart algorithm that ease modelling in environmental studies.

In short, this study emphases on integrating Gaussian Plume algorithm alongside air flow and pollutant dispersion solver based on CFD model. Additional unique features on CFD model mesh generation for automatic building construction from satellite image is developed using building footprint detection and height estimation technique.

1.2 Problem Statement

In standard practice, Gaussian Plume model (regional estimation of air pollution level in EIA analysis) and CFD models (detailed air flow and pollutant dispersion simulations) are used in different applications and purposes. Gaussian Plume models generally applied in predicting ground concentration from industrial stack release in EIA analysis, whereas CFD models are used to attain detailed wind flow and pollutant simulation in urban areas. By having both models in the same algorithm, town planners will be able to find areas in urban industrial park with severe pollutant concentration and further investigate those regions using CFD model. In order to achieve this, a new algorithm are developed from scratch as both models are developed separately due to dissimilar approaches, assumptions, fundamental principles, governing equations and parameters used in the models. The present algorithm is not restricted to provide regional estimation of air pollution level (as in commercial software packages), but also able to present detailed wind distribution, pollutant dispersions and entrapment zones within respective areas that is crucial to monitor in the long run. Existing commercial atmospheric dispersion software is not capable to do so.

For air pollutant simulation across complex building structures, building data such as stored in GIS are hard to acquire, expensive in cost and usually less accurate for small cities and undeveloped areas. GIS data require manual update on regular basis to stay updated with newly developed areas and a large number of GIS personnel are needed to cover data for all cities. In addition, manual data update practice in GIS may cause human error as well as labour and time consuming. As for current CFD commercial software, users need to remodel buildings and obstacles which results in repetitive and tedious process for air pollutant mapping in town planning application. To our knowledge, an effective tool that is able to automatically produce CFD mesh from satellite image integrated with air pollutant simulation solver for urban planners is still unavailable. Besides, studies on CFD analysis on high concentration zones predicted by Gaussian Plume model within urban industrial park is lacking in the literature.

For that, present study integrates both Gaussian and CFD model with automated building generation algorithm from satellite image and apply the algorithm in high pollutant concentration zone in urban industrial park.

1.3 Research Objectives

The objectives of the present study are:

(a) To integrate urban building generator from satellite image, Gaussian Plume and CFD model.

(b) To evaluate performance of the developed satellite image urban building generator, Gaussian Plume and CFD algorithms.

(c) To analyse wind flow, air pollutant dispersion and critical zones at high ground-level concentration areas in urban industrial park.

1.4 Significance of Study

This study improves conventional air pollutant regulatory model by providing detailed analysis of wind flow and pollutant dispersion process at high concentration zones predicted by the Gaussian plume model. It enhances usage of CFD model alongside Gaussian Plume model for air pollutant modellers by providing relatively accurate and fast CFD solver using the least expensive turbulence model coupled with automated CFD urban mesh generator from satellite image. As a result, an integrated Gaussian and CFD solver is produced that is practical for regulatory use united with additional capabilities to get detailed simulation on highly concentrated areas. This study encourages the use of CFD model in EIA analysis to complement data provided by Gaussian Plume model.

1.5 Scope of Study

In this study, Gaussian Plume and CFD model are used. In the CFD model, Fractional Step Method is used as the steady-state wind flow solver, Prandtl Mixing Length model is used for turbulence calculation. In urban building generator algorithm, colour separation technique is used for building detection process whereas shadow length estimation is used for building footprint height extrusion.

This study focuses on simulation of non-reactive air pollutants (SO_2, NO_2 and PM_{10}) released from major industrial stacks in Pasir Gudang Industrial Park, Johor towards nearby residential areas. In the simulation, only industrial stacks emissions are considered without background pollutant concentration (previous day, month and year concentration) and external pollutant sources such as vehicular emissions and construction sites are not taken into account. In this study, the air pollutants are assumed to be released towards a completely clean ambient atmosphere thus the ground pollutant concentration exerted to the nearby residential areas in Pasir Gudang are only contributed by respective industrial stacks emissions.

It is assumed that all buildings are on flat terrain without elevation (hills and mountains), no trees and bushes are considered and all buildings have flat rooftops in which building geometries are dependent on their footprint shapes for building extrusion process.

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