Modelling airborne dispersion for disaster management

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Abstract. Industrial disasters, like any other disasters, can happen anytime, anywhere and in any form. Airborne industrial disaster is a kind of catastrophic event involving the release of particles such as chemicals and industrial wastes into environment in gaseous form, for instance gas leakages. Unlike solid and liquid materials, gases are often colourless and odourless, the particles are too tiny to be visible to the naked eyes; hence it is difficult to identify the presence of the gases and to tell the dispersion and location of the substance. This study is to develop an application prototype to perform simulation modelling on the gas particles to determine the dispersion of the gas particles and to identify the coverage of the affected area. The prototype adopted Lagrangian Particle Dispersion (LPD) model to calculate the position of the gas particles under the influence of wind and turbulent velocity components, which are the induced wind due to the rotation of the Earth, and Convex Hull algorithm to identify the convex points of the gas cloud to form the polygon of the coverage area. The application performs intersection and overlay analysis over a set of landuse data at Pasir Gudang, Johor industrial and residential area. Results from the analysis would be useful to tell the percentage and extent of the affected area, and are useful for the disaster management to evacuate people from the affected area. The developed application can significantly increase efficiency of emergency handling during a crisis. For example, by using a simulation model, the emergency handling can predict what is going to happen next, so people can be well informed and preparations works can be done earlier and better. Subsequently, this application helps a lot in the decision making process.

1. Introduction

1.1. Airborne Dispersion

Air particles and gases exist as fluid in the environment; the substance has flexible form and is highly dynamic. Gases particles can take on any shape, the dispersion of the gas particles are dependent on internal factors as well as external factors. Dispersion of gases are evolved through three phases – rapid phase of internal slumping, intermediate entrainment phase and final phase of passive diffusion [3].

During the first phase – rapid phase of internal slumping, the movement of the gases are driven by the excessive hydrostatic forces due to high gas density compared to the surroundings. The dispersion pattern of the gas particles in this phase is in random direction, causing the particles to be pushed outwards from within. During the second phase – intermediate entrainment phase, the activity of the gas particles is directly influenced by the entrainment effects of the gas particles, in which the gases with lower density will be entrained into those with higher density. During the third phase – passive diffusion phase, the activity of the gas particles are fully dependent on the external forces such as wind...
and pressure [3]. The gas particles do not move on its own anymore in this stage, they remain stationary at the same spot until carried away. Various chemical substances are used in the industry for manufacturing and consumption purposes, some common names are such as naphthalene (C10H8), benzene (C6H6) and ammonia (NH3). These chemicals were commonly found in the manufacturing and electronic industry, naphthalene and ammonia are widely used and stored at Pasir Gudang industrial area, especially around the port area. These gases were stored in pressure tanks under high compressions, thus leakage can occur when the facilities were worn and old. Besides that, there are many other flammable and explosive gases stored in the industrial area such as propane and liquefied petroleum gas, these substance can be easily ignited and can cause explosions when heated, especially under hot and humid weather in tropical countries such as Malaysia. These chemicals are stored in storage tanks in abundance; the disaster can last up to few days and have a severe effect to the environment if it is not contained properly.

1.2. Modelling Air Particles Dispersion

Many gases are colorless and odorless, this makes the presence of the gas hard to be detected, and thus it is hard to predict the dispersion of the gas particles and the direction of the spread of the disaster. This makes the disaster management hard to be carried out as the emergency handling unit has to search for the whole area to identify the gases, the responses would be delayed as well in this case, causing the disaster handling to be slow and inefficient. In this case, modeling the dispersion of the air particles can be very useful for the emergency handling job. The simulation can be carried out using mathematical algorithm to predict the whereabouts of the gas particles and the most likely direction the spreading is heading to. Conventional methods such as Gaussian mathematical methods were widely used to model the dispersion of the liquid in the past; however this might not effectively model the dispersion of the gas particles as Gaussian models and Eulerian models assume the external variables in space and time to be global and constant all the time [7].

Lagrangian particle dispersion (LPD) is more suitable to be used to model the dispersion of air particles, this algorithm is able to compute dynamic input data such as wind speed and direction, which changes instantly in the real world [11][12]. Lagrangian particle models compute trajectories of a large number of so-called particles to describe the transport and diffusion of tracers in the atmosphere [1]. Many researches about simulation of gas leakage were done in the past, noticeably the most popular one was the Bhopal gas tragedy in India which occurred in 1984 [5][6][7][8]. These researches use numerical methods such as K - Closure meteorological model [7], Lagrangian model [9][10] and simulation models such as the Haddon matrix analysis [5] to simulate the aftermath of the disaster. By using the numerical models, the research can estimate the number of affected peoples and the properties and also the area covered by the leakage; these models are also useful to predict the factors and consequences of the event as well as the dispersion of the gases in graphical forms.

However, the researches in the past simulate the model in a mathematical coordinate system, there were no integration of GIS into past models so that the analysis were done in a projected coordinate system. So, there is a need to create a GIS integrated model to simulate situations related to location and environment.

1.3. Disaster Management

Disaster management is a set of precautionary procedures and protocols to be applied to avoid and to deal with disasters, it can be used as a guideline for pre-event preventions or post-event emergency handling. Disaster can be found almost everywhere, and it is often triggered by various factors, such as natural disasters, human mistakes and bad maintained facilities. One good example is gas leakages at industrial area due to corrosion of storage tanks by acidic substances. Industrial gas leakage can be fatal and can inflict permanent damage to the peoples and objects nearby, especially when the gases are highly toxic, flammable and highly reactive with other materials causing a chain effect to occur. Disaster management is important especially in medium and heavy industry area, these areas are
always in larger scale and there are more chemical substances being stored, so the risk of disaster is higher and needs a better disaster management team to handle during an outbreak.

In Malaysia, the disaster risk indicator is classified into three categories; tier 1, 2 and 3 according to Department of Social Welfare Malaysia (JKM), these classes identifies the critical level of the disaster and to guide the decision makers to figure out suitable solution for the problems. The description of the classes is as shown in Table 1.

| Tier  | Description                                                                 |
|-------|-----------------------------------------------------------------------------|
| Tier 1 | Local incident that is manageable and has no potential to spread. It is not very complex and may result in loss of life and property is small. This disaster did not affect the daily activities of the local population at large. Authorities at District Level have the ability to control and overcome this incident through agencies in the District Level with or without outside help are limited. |
| Tier 2 | The more serious incident covers a large area or more than two (2) Districts and has the potential to spread. Likely to lead to loss of life and a lot property damage. This incident also destroy infrastructure and affect daily activities of life. Is more complex and complicate than Level 1 Disaster in term of search and rescue efforts. Need and be able to be operated by the Authority at State level without or with limited outside help |
| Tier 3 | Disaster incident resulting from Level 2 is more complex or cover a larger area or more than two (2) states. Need and be able to be operated by the Authority at the Federal level without or with assistance from abroad. |

### 1.4. History of Gas Leakage in Malaysia

Gas leakage is a common disaster that happens in Malaysia, there are various causes of gas leakage such as operational blunders, poorly maintained facilities and equipment, and natural disasters such as earthquake and thunder strike. Some of the larger scale airborne disasters are the Petroleum Sdn. Bhd. gasoline tank explosion and the ammonia gas leakage in Labis, Johor.

#### 1.4.1. Petronas Gasoline Tank Explosion

Petronas is an oil and gas company which is located at Johor port in Pasir Gudang industrial area. This catastrophe happens on 24th April 2006 where eight of the gasoline storage tanks own by Petronas caught fire from thunder strike and black fumes appears at the area. The fire continue to burn for three days before being put out, it is one of the largest scale disaster in Pasir Gudang history. This disaster is a tier 3 disaster where neighbouring countries such as Singapore were helping to contain the fire. Lots of black fumes (carbon monoxide) due to the burning of gasoline had been released to the environment during the fire. The smoke can affect the health of residents that reside at that area, as well as pollute the rivers and crops nearby, causing losses to the nearby industries and affecting the operation of the nearby businesses. The smoke has spread to nearby village; Kampung Pasir Putih which is located north eastern of Pasir Gudang [4].

#### 1.4.2. Labis Ammonia Leakage

Another large scale airborne disaster happens at Labis, Segamat, Johor where 300 tonnes of Ammonia (NH3) gas leaks to the surrounding areas from an illegal dumpsite of a company from Malacca. 300 families were evacuated from ground zero; Kampung Sungai Gatom and more than 100 factory employees were barred from entering the area to work as the company is located in that area. This incident has brought destructive aftermths to the agricultural industry nearby the dumpsite where most of the plantations turned yellowish due to Ammonia poisoning [10]. It is difficult to contain the incident as the Ammonia gases are colorless, they were invisible to the naked eyes. One way to detect the presence of the Ammonia gas is by smelling
because Ammonia gas is pungent in nature, so the response to the incident will be delayed because they need to wait for reporting from the peoples.

1.5. Modelling Air Particles in the Past and Today

Today, with the aid of advanced hardware capabilities and processing power, the modeling of the air particles has undergone a drastic improvement by integrating GIS technologies and mapping capabilities. Simulations can be carried out using live feed data from various sources and the processing power of hardware can cope with the huge amount of data exchange through the use of high bandwidth internet connections.

Therefore, the following question arises: How does today technology helps in improving emergency handling? Since the web platform and technologies has improved a lot after so many years, how can people utilize the technology to perform real time analysis and to disseminate information to the public in a quicker and more efficient way? By integrating GIS and web technology into emergency handling, the efficiency and the visualization of the emergency handling can be greatly improved. This allows the user to have a better understanding and accurate interpretation of the information as well as to disseminate the critical information to the public in the shortest delay. Therefore, integration of GIS and web technology undeniably could help improve emergency handling and to hasten the decision making process.

This paper is structured in the following order: first, a brief explanation of airborne dispersion and disaster management. Section 2 discuss on the modeling the airborne particles. Section 3 explains the algorithms used to perform the calculation of the dispersion of the air particles. The operation and output are presented in Section 4 and concluding remarks in Section 5.

2. Modeling Airborne Particle

To simulate the dispersion of air particles, an application prototype has been developed to compute the characteristics of air particles and the way air particles move around under the influence of wind.

Due to the dynamic characteristic of the wind, the dispersion of air particles in the air can be highly fluctuating. In order to model the wind, a simulation model which can accept dynamic parameters is needed, Lagrangian particle dispersion model is suitable to be used to simulate the movement of the air particles as the Lagrangian particle dispersion model calculates the next displacement of the air particles based on the previous position, so this model is suitable to be used in situation where highly dynamic data input is required.

The concept of the application is to make use of the web services from third party service providers such as Google and Yahoo! as the data provider so that the data input into the model can be updated by itself on real time and the changes to the data are handled automatically by the application.

2.1. System Design

The application prototype has a three tier infrastructure as shown in Figure 1, which is database, server and client side infrastructure. The application is distributed into three parts, so that the performance can fully utilize the hardware resources and web bandwidth.

![Figure 1. System Architecture](image)
2.2. **Web Server and Network Database**

The application uses XAMPP hosting package to host the web system. XAMPP is an open source web hosting package that provides a variety of function and services such as Apache web server and MySQL database. The application uses the landuse data of Pasir Gudang, Johor and the Places-of-Interests (POI) data such as location of police station, hospital and express terminal to perform the analysis. The data geometry were stored in the MySQL Spatial database and loaded into the map view by using the Google Maps API map feature function. The landuse cover was created in the map view as polygon and the POI data was displayed in the map view as points. The geometric shape of the landuse data is as shown in Figure 2.

![Figure 2. Landuse and POI data in Pasir Gudang, Johor](image)

The attributes and the shapes of the landuse data and POI data were stored in the MySQL database as geometry data, the geometries of the polygons are stored as multipolygon spatial format which is supported natively in MySQL.

2.3. **Application Flow Chart**

The flow of the application is as shown in Figure 3.

![Figure 3. System application flowchart](image)
2.4. Third Party Services and Data Feeds
The application prototype was developed on the web platform; the application makes use of existing Web Map Services (WMS) and weather RSS feeds as the data input for the parameters in real time. Google Maps API version 3 was used as the WMS map mashup of the application, this is the latest version of WMS from the browser machine company which has a stripped down architecture and is quicker in response to the mobile browsers. The weather RSS feeds were reading the data from Yahoo! Weather feeds by using its API, by using this method, the wind speed and direction can be updated every second. The Yahoo! Weather RSS feed is formatted to return the wind speed, bearing and wind direction.

There are a few analysis being carried out at the server side, this including the determination of the movement of the air particles under the influence of the wind and the conversion of the displacement of the particles from wind speed (meter per second) to the map view which is in decimal degree. The determination of the movement of the particles under the influence of wind speed is calculated by using trigonometry where the X and Y components forms part of the triangles and the speed can be calculated by using Pythagoras theorem. The condition of the algorithm is as shown in Figure 4.

![Figure 4. Trigonometry to determine wind component](image)

The unit of wind components is in meter per second; this means that the wind components are in metric units, metric units cannot be directly integrated into the Google Maps view which is using decimal degrees (Coordinate System: World Geodetic System 1984 (WGS84)). In order to integrate the wind components into the map view, a conversion has to be carried out to convert the wind vector components (speed in north-south and east-west direction) from metric units into decimal degree; this requires conversion from metric coordinate system Malaysian Rectified Skew Orthomorphic (MRSO) to Malaysian Revised Triangulation (MRT) to WGS84.

2.5. Modelling Gas Leakage
The application applied mathematical algorithm to model the dispersion of the air particles and the direction the particles are heading to. The mathematical algorithm used was the Lagrangian particle dispersion model.

In order to model the scenario of the gas leakage, the application would randomly populate gas clouds (point feature) into the map view in a 15 meters radius buffer from the incident point (disaster source). This is to simulate the movement of the gas particles from the first to phase of dispersion, the rapid phase of internal slumping and the intermediate phase of entrainment of the particles which will
push the particles outwards into a certain distance in all direction, so the particles are distributed randomly at this stage. The particles will then move to other directions based on the wind parameters feed in by Yahoo! Weather. To model this movement, the application utilizes the Lagrangian particle dispersion model to calculate the individual displacement of the particles in the map view.

3. Applying the Algorithms

3.1. Lagrangian Dispersion Model (LPD)

The Lagrangian particle dispersion model was designed to compute the individual displacement of the gas particles along range and mesoscale environment [2]. The algorithm simulates the dispersion and the trajectories of the air particles by using the carrier vector components. The dispersions are calculated according to:

\[
\begin{align*}
X(t + \Delta t) &= X(t) + U(t) \times \Delta t \\
Y(t + \Delta t) &= Y(t) + V(t) \times \Delta t
\end{align*}
\]  

where,
- \(X\) = longitudinal position of the air particle
- \(Y\) = latitude position of the air particle
- \(t\) = the current time
- \(\Delta t\) = change of time
- \(U\) = the east-west vector component (speed) of the wind
- \(V\) = the north-south component (speed) of the wind

The Lagrangian particle dispersion model makes use of the wind component to simulate the trajectories of the air particles. The position of the particles at time \(t + \Delta t\) is calculated based on the previous position of the particles at time \(t\). Thus this algorithm is suitable to be used to model the dispersion of the air particles as the calculation uses different parameter from time to time, this is suitable to the characteristics of the wind which is dynamic and changes all the time. The movement of the particles is as shown in Figure 5, the particles move to bearing 30 degrees as follow to the wind direction.

![Figure 5. Movement of air particles in LPD](image)

The movement of the particle in close up would be show the evolution of the air particles from one position to the next position. Each particle is retained and the next position of the air particle under the influence of the wind is calculated using the Lagrangian particle dispersion model.
3.2. Convex Hull
Convex hull is a mathematical algorithm used to calculate the minimum bounding polygon that contains points X given a set of point X. This means that the convex hull algorithm is used to identify the outermost points of a given set of points, the convex points and connect the points to form a polygon which is able to contain all the other points in the polygon.

The convex points were calculated according to a logical loop where the algorithm loops through all the points in the given point set. The algorithm would then determine whether the point is the point located at the left most position as it loops through the set of points as shown in Figure 6(a).

![Figure 6](a) Left: Given a set of point. (b) Right: The convex polygon

The points will be looped through one by one to determine the left most points. By looping through the points, the algorithm determine the minimum and maximum latitude and longitude position of the points, if it has either a maximum or a minimum position, then it is a convex point. The result of the convex hull is as shown in Figure 6(b).

3.3. Performing GIS Analysis (Intersection) using MySQL Spatial
The position of each of the nodes of the convex polygon was sent to the database server to perform an intersection between the convex polygon and the landuse polygon layer. The coordinates of the points send were structured into a multipolygon format as shown in Figure 7 to integrate with the MySQL Spatial syntax.

![Figure 7](Multipolygon data representation in MySQL Spatial format)

The intersection is carried out by using the following SQL Spatial syntax:

```sql
SELECT intersects (GeomFromText("the convex polygon points"),
GeomFromText("ogc_geom column")) FROM zone;
```

4. Result and Validation

4.1. Application Output
The analysis of the application is to determine the coverage area of the air particle over the Pasir Gudang area to determine the effects of the disaster to the surrounding environment. The analysis involves intersecting the convex hull polygon to the landuse cover data of Pasir Gudang and the POI data. In order to determine the effect of the disaster to the surrounding environment, the convex hull polygon was overlaid on top of the landuse cover, then an intersection process was carried out to retrieve the intersected pieces of land polygon, this results give us the affected area of the Pasir Gudang industrial area. Following the intersection, the application will also calculate the extent of the affected area (in km²) and the percentage of the affected area compared to the total landuse parcel.

The application also produce a suggestion to the user the nearest evacuation point from the incident area, the application calculates the distance of each POI from the incident area and return the nearest one to the user. The dispersion of the air particles follows the wind direction, the wind component is 3.333 m/s to bearing 40 NNE as shown in Figure 8(a), Figure 8(b) and Figure 8(c), we can see that the dispersion of the air particles flow from the source point towards the north east direction, following the trajectories of the wind.

4.2. Airborne Dispersion Validation

In order to validate the results of the simulation model, comparison of results from the developed prototype has been made with the results obtained from an online simulation application called HYSPLIT Air Dispersion Model developed by National Oceanic and Atmospheric Administration (NOAA). The HYSPLIT dispersion model uses Lagrangian Particle Dispersion model to compute the dispersion of the air particle as well [13]. The result from HYSPLIT program is an hour long of processing data, which is simulated using the archived weather data and then exported to ESRI Shapefile along with a GIF image map. The GIF image of the result is shown in Figure 9a and the shapefile is opened in QGIS software as shown in Figure 9b.

Figure 9. (a) Left: GIF map results from HYSPLIT and (b) Right: HYSPLIT result in vector format (Shapefile) overlay with Google Maps imagery in QGIS
For comparison, a set of air particle points (from LPD model) have been generated using the developed prototype simulation model for the period of one hour, the results were overlaid on top of the HYSPLIT result. The distance covered by the HYSPLIT result is 14.9km while the result generated by the prototype simulation model is 14.2km, thus the results were identical to each other up to 95%. Figure 10 shows the overlaid comparison of both results for 1 hour duration.

**Figure 10.** Comparison of results from HYSPLIT (NOAA) and the developed prototype

For visual inspection, the validation result is divided into three zones, namely the zoom (a) zone as shown in Figure 11(a) with high concentration gases, zoom (b) zone as shown in Figure 11(b) where the concentration starts to spread outward and zoom (c) as shown in Figure 11(c) where the gases are in various concentrations.

**Figure 11.** (a) Left: Zoom (a), the concentration of the gases at ground-zero, (b) Middle: Zoom (b), concentration of the gases start to decline and the dispersion pattern appears to be diverged outwards and (c) Right: Zoom (c), dispersion pattern diverged outwards and gases are in various concentrations.

In Figure 11(a), the result of the model is same as the result produced by NOAA, this is because the concentration of the gases are the same. While in Figure 11(b) the concentration of the gases start to decline and the dispersion pattern appears to be diverged outwards. In Figure 11(c) the dispersion pattern of the results are not the same because the NOAA model takes into consideration the decline in gas concentration; while the developed prototype model only simulate the air particles in the same concentration throughout the period, so the results appear to be in constant width without diverging outwards. However, the results of both models appear to be quite similar to each other.
5. Conclusion

In conclusion, the dispersion of the air particles in the environment is usually hard to be traced, so it is important to have modeling system to predict the trajectories of the air particles in the air. Through the use of the modeling system, the authorities can be well informed of the direction of dispersion of the air particles and affected area of Pasir Gudang. This can help a lot in decision making to save lives and to evacuate peoples to safety during a disaster outbreak. Hopefully by using this application, the emergency handling in Pasir Gudang industrial area can be improved and more life can be saved.

Besides that, the model can also be applied to other field besides airborne disaster such as to determine the dispersion of air pollution and dispersion of radioactive materials from factories, as long as the subject is airborne and can be easily carried away by wind.

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