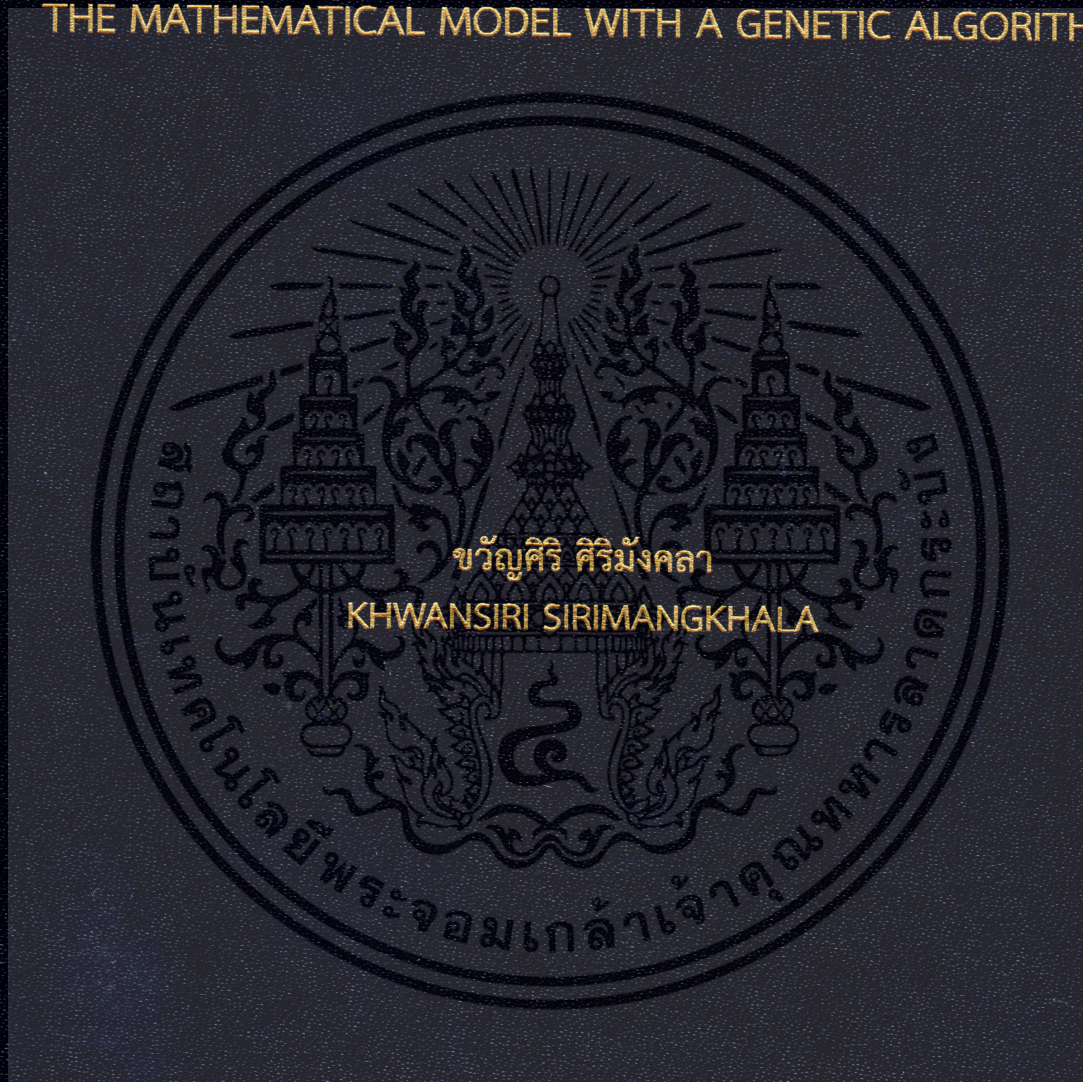


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และขั้นตอนวิธีเชิงพันธุกรรม

SIMULATION OF GREENHOUSE GASES IN LANDFILL USING  
THE MATHEMATICAL MODEL WITH A GENETIC ALGORITHM



วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตร  
ปริญญาปรัชญาดุษฎีบัณฑิต สาขาวิชาคณิตศาสตร์ประยุกต์  
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สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง

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เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้งานเพื่อการศึกษาเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า  
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SIMULATION OF GREENHOUSE GASES IN LANDFILL USING  
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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE  
DEGREE OF DOCTOR OF PHILOSOPHY IN APPLIED MATHEMATICS  
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2019

เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้ภายในห้องเรียนเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า  
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### บทคัดย่อ

การฝังกลบเป็นวิธีการกำจัดขยะที่ได้รับความนิยมทั่วโลกเนื่องจากเป็นวิธีการที่มีต้นทุนต่ำ แต่อาจก่อให้เกิดข้อเสียได้หากไม่มีการควบคุมการปล่อยก๊าซเรือนกระจก ได้แก่ ก๊าซมีเทนและก๊าซคาร์บอนไดออกไซด์ ซึ่งเป็นก๊าซที่เกิดได้ในอัตราส่วนสูง งานวิจัยฉบับนี้นำเสนอเปรียบเทียบข้อดีข้อเสีย และข้อจำกัดของแต่ละแบบจำลองทางคณิตศาสตร์และการจำลองทางคอมพิวเตอร์ที่นิยมใช้ในระบบฝังกลบ นอกจากนี้ยังมีการศึกษาตัวแปรที่มีผลต่อการเกิดก๊าซเรือนกระจกในระบบฝังกลบขยะ โดยกระบวนการทางเคมีในระบบฝังกลบแบบปิดถูกนำมาพิจารณา เพื่อสร้างและวิเคราะห์แบบจำลองทางคณิตศาสตร์

**คำสำคัญ** : การฝังกลบขยะ ก๊าซเรือนกระจก แบบจำลองการปล่อยก๊าซมีเทน การจำลอง ขั้นตอนวิธีเชิงพันธุกรรม

<b>Thesis Title</b>	Simulation of Greenhouse Gases in Landfill Using The Mathematical Model with A Genetic Algorithm
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<b>Degree</b>	Doctor of Philosophy (Applied Mathematics)
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### Abstract

Landfill has been widely used in many countries for the final disposal of solid waste material due to its economic advantages but landfill may release significant greenhouse gas: methane and carbon dioxide. This research presents mathematical model and computer simulation widely used for landfill site which compare advantages, disadvantages and limitation of each model. Moreover, the dynamic characteristics of greenhouse gases generated from the closed landfill system were studied. The chemical reaction processes involved are considered and a mathematical model is formulated and analyzed.

**Keywords:** Landfill; Greenhouse gas; Methane emission model; Simulation; Genetic Algorithms

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เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้งานเพื่อการศึกษาเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า  
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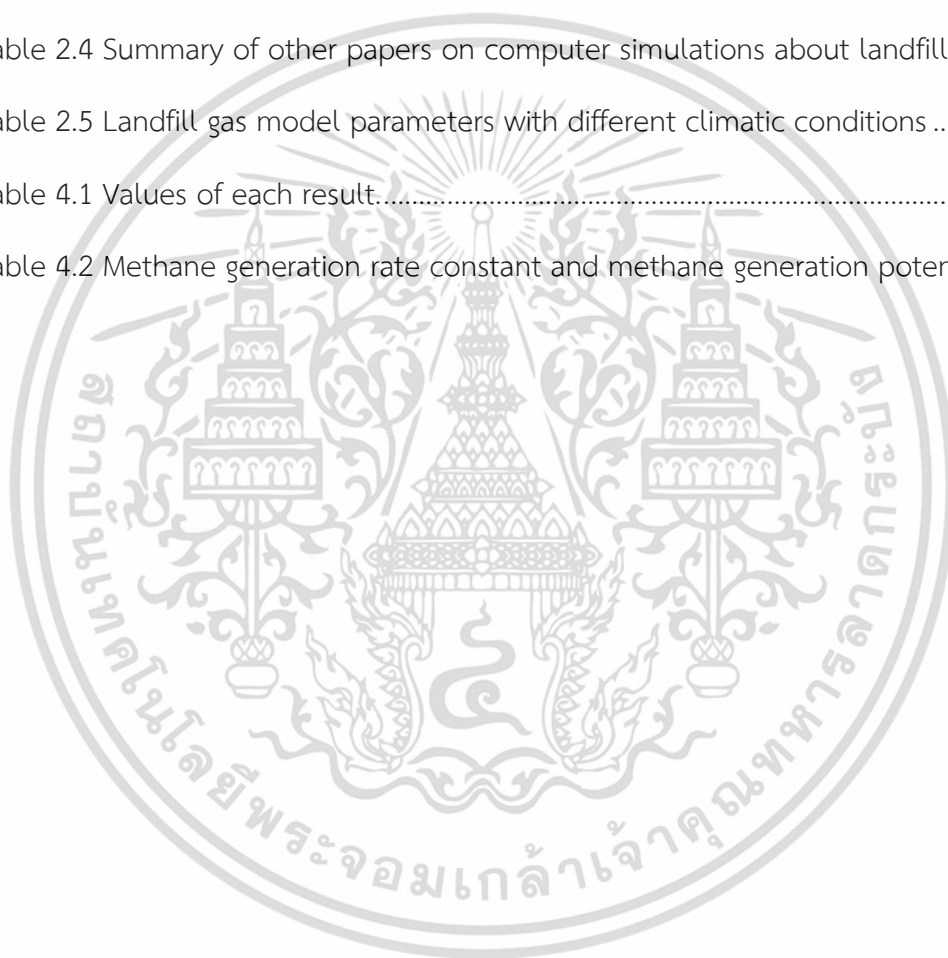
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เอกสารนี้เผยแพร่เพื่อการศึกษาเท่านั้น ห้ามทำซ้ำโดยไม่ได้รับอนุญาต

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# Chapter 1

## Introduction

### 1.1 Research Motivation

Since rapidly increasing populations and unprecedented urbanization rates, waste generation is growing rapidly, particularly in cities and especially in developing countries (Yang et al., 2018). It was estimated 1,000,000 metric tons of waste is generated daily around the world. Mismanagements effect to human health because of contaminated waste and gas emission from waste. Moreover, waste is causing germs which if it is mismanagement it maybe leads to the spread of disease by insects. Proper waste management eliminates adverse impacts on the environment and human health (Dawane et al., 2015). Waste is creating a problem with some cancer for the population living near landfill sites (Giusti, 2009).

Effective waste management, especially of toxic material, is a major challenge for global sustainable development. A range of methods is available for the disposal or treatment of waste including incineration, composting, recycling, and landfill. Landfill remains the most widely used approach in the developing world due to its low cost. However, improper management can result in major health and environmental problems (Marion et al., 2008).

Waste treating worldwide in Figure 1.1 which it divides by different regions. As we can see from the graph, open dumping and landfill are the most in each region (The Statistics Portal, 2018). Moreover, a major part of this waste is treated by landfill which has its influences over land and environment (Dawane et al., 2015).

There are two majors to consider in landfill: leachate and landfill gas. Leachate is the release from a sanitary landfill consists mainly of leachate which has become the subject of recent interest as strongly polluted wastewater and biogas, which is a resource that can be utilized for energy production (Renou et al., 2008). Landfilling is one of the most commonly adopted technologies for refuse disposal (Tchobanoglous and Kreith, 1994). The landfill methods continue to be widely used

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economic advantages (Renou et al., 2008). However, a lot of greenhouse gases, especially CO<sub>2</sub> and CH<sub>4</sub>, are products in landfill waste management process.

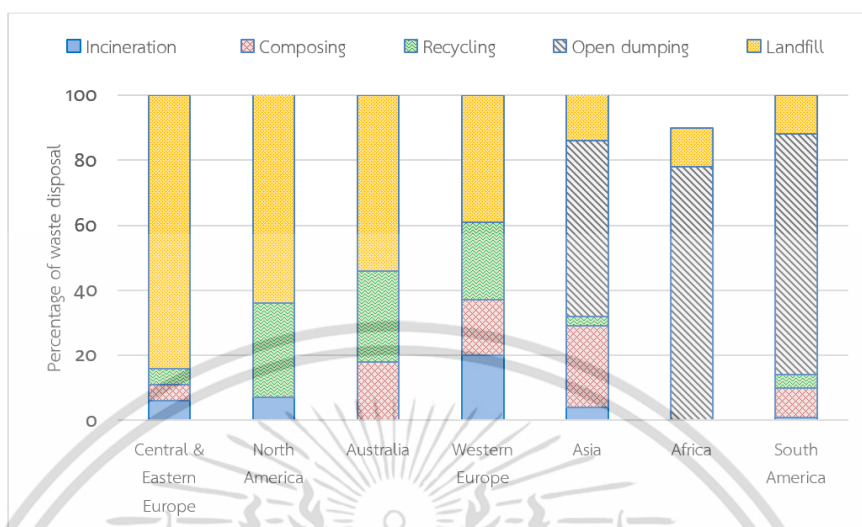


Figure 1.1 Waste disposal worldwide by region (Modified from The Statistics Portal).

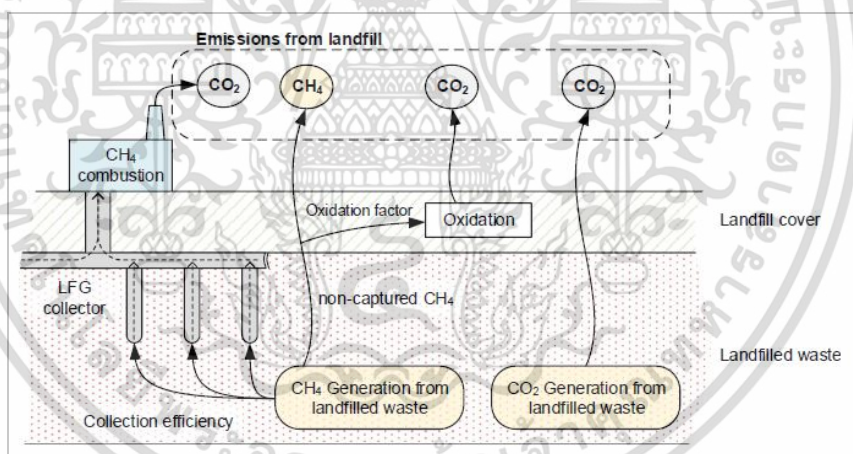


Figure 1.2 Landfill gas generation [9]

Therefore, to reduce greenhouse gases, governments around the world are encouraging projects that turn landfill gas into electricity. It is available worldwide to collect and utilize this valuable renewable energy source for power generation. Landfill methane is abundant and readily to this source. The potential to produce 2,700 MW of electric generating capacity in the United States alone and 9,000 MW worldwide. Figure 1.2 represents landfill gas generated from the waste decomposition which carbon emissions depend on the methane concentration.

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Landfill gases are mixtures of several gases with its main constituents being methane and carbon dioxide, are the main gases produced by landfill process approximately 50 – 55% , and 45 – 55% respectively, while other gases are less common (Landfill Methane Outreach Program, 2016). It is an alternative method concerning methane and carbon dioxide emission control which can be created by the reaction of certain chemicals presented of waste. This process can be divided into two main parts; it is aerobic and anaerobic decomposition which mainly generates methane and carbon dioxide. Methane is regarded as one of the most important greenhouse gases because its global warming potential of methane is 28 times higher than carbon dioxide (Tchobanoglous and Kreith, 1994; Globler et al., 2014; Jha et al.,2008; Chen et al., 2008; Pachuri et al., 2014). Hence, studying the generation of methane and carbon dioxide is one of the interesting research areas especially from the greenhouse gas viewpoint (Renou et al., 2008; Themelis and Ulloa, 2007). It's known that the occurrence of carbon monoxide (CO) and its reaction can eventually perform chemical reactions to other gases such as CO<sub>2</sub>, CH<sub>4</sub>, and O<sub>3</sub> thereby generating greenhouse gases and cause global warming (Seinfeld and Pandis, 1998; Letcher and Vallero, 2011; Raub et al., 2000). Global warming is one of the several environmental impacts derived from solid waste management options. Several research works focused on the landfill system-related gases in connection with the environmental problem (Lisk, 1991).

## 1.2 Objectives of the study

- 1) To compare the advantages, disadvantages, and limitations of landfill models to improve the greenhouse gas emission model by modeling and simulation with a genetic algorithm.
- 2) To present mathematical model supported the physical phenomena of the landfill gas system which explain the transition of CO, O<sub>2</sub>, H<sub>2</sub>, CO<sub>2</sub>, and CH<sub>4</sub>.

## 1.3 Scopes of the study

- 1) For the first objective, we focus on the behavior of greenhouse gases generated from the closed landfill system which anaerobic digestion process.

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- 2) For the second objective, the involved chemical reaction processes and mathematical model for model formulation and analysis. The behaviors of the key greenhouse gasses namely  $\text{CO}_2$  and  $\text{CH}_4$  are carefully studied. Moreover, other parameters such as  $\text{CO}$ ,  $\text{H}_2$ , and  $\text{H}_2\text{O}$  are investigated. Note that this system is not focused on  $\text{N}_2$  and  $\text{O}_2$  because of anaerobic digestion.

#### 1.4 Benefits of the study

- 1) Modeling and simulation with genetic algorithms give an attractive result.
- 2) The mathematical model for a close landfill system is obtained to confirm physical phenomena.



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## Chapter 2

# Theory and Literature Reviews

Landfilling is one of the most commonly adopted technologies for refuse disposal (Tchobanoglous and Kreith, 1994). The landfill methods continue to be widely used in different countries for the final disposal of solid waste material due to its economic advantages (Renou et al., 2008). However, a lot of greenhouse gases, especially CO<sub>2</sub> and CH<sub>4</sub>, are products in landfill waste management process. Therefore, to reduce greenhouse gases, governments around the world are encouraging projects that turn landfill gas into electricity. It is available worldwide to collect and utilize this valuable renewable energy source for power generation. Landfill methane is abundant and readily to this source. The potential to produce 2,700 MW of electric generating capacity in the United States alone and 9,000 MW worldwide.

### 2.1 Landfill process

Typically, the decomposition of refuse to methane in landfills is a microbial mediated process that requires the coordinated activity of several trophic groups of bacteria (Uisung et al., 2017; Daniel, 1993). The composition of the gas produced changes with each of the four phases of decomposition.

#### Phase I – Aerobic phase (Hydrolysis)

During the first phase of decomposition, aerobic bacteria – bacteria can survive and grow in an oxygenated environment. It consumes oxygen while breaking down the long molecular chains of complex carbohydrates, proteins, and lipids that comprise organic waste. As you can see from Figure 2.1 (Das et al., 2016), there are 80% N<sub>2</sub> and 20% O<sub>2</sub> at the beginning. Both oxygen and nitrate are consumed. The primary by-product of this process is carbon dioxide and hydrogen. Phase I continues until available oxygen is depleted. The gas composition will be nearly 25% CO<sub>2</sub> and 10% H<sub>2</sub>.

#### Phase II – Anaerobic phase (Acidification)

Phase II decomposition starts after the oxygen in the landfill has been used up. Bacteria convert compounds created by anaerobic bacteria (a process without oxygen requirement) into acetic, lactic, and formic acids and alcohols such as methanol and ethanol. The landfill becomes highly acidic. The gaseous by-products of this process are CO<sub>2</sub>

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and  $H_2$  anaerobic conditions;  $N_2$  content in gas decreases during this phase and is nearly completely displaced at the end of the phase; pH is decreasing. As you can see from Figure 2.1 carbon dioxide increase from 25% to 65% at the end of phase II which is a peak of it in this system. Hydrogen increases slowly between 10 – 20 % (Oonk and Boom, 1995).

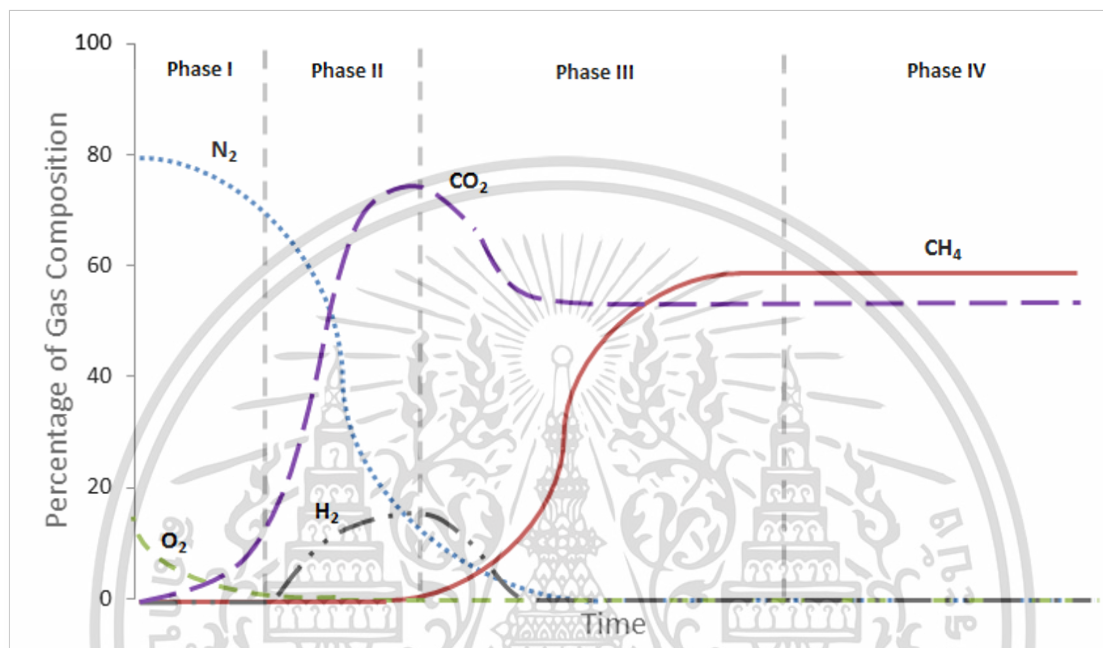


Figure 2.1 Changes in typical landfill gas composition after waste placement

### Phase III – Initial methanogenic phase (Acetogenesis)

This process causes the landfill to become a more neutral environment in which methane-producing bacteria began to establish themselves. Acid-producing bacteria create compounds for the methanogenic bacteria to consume. Methanogenic bacteria consume carbon dioxide and acetate. In this phase, there is a rapid increase in the rate of methane production to some maximum value of approximately 50 percent of gas composition. Increase of  $CH_4$  production associated with a decrease of  $CO_2$  (drop from 65% to nearly 50%) and  $H_2$ ; pH is slowly increasing.

### Phase IV – Stable methanogenic phase (Methanogenesis)

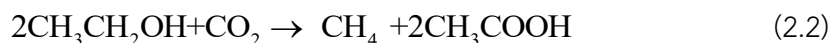
Phase IV decomposition begins when both the composition and production rates of landfill gas remain relatively constant. Landfill gas usually contains approximately 50% to 55% methane by volume, 45% to 50% carbon dioxide, and 2% to 5% other gases. Oxygen, เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้งานเพื่อการศึกษาเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า ไม่ว่าจะกรณีใดๆ ทั้งสิ้น อีกทั้งห้ามมิให้ตัดแปลงเนื้อหา และต้องอ้างอิงถึงเจ้าของเอกสารทุกครั้งที่มีการนำไปใช้

hydrogen and nitrogen decline as the landfill moves through the four phases. Gas is produced at a constant rate in Phase IV, typically for about 20 years; however, gas will continue to be emitted for 50 or more years after the waste is placed in the landfill (IPCC, 2006). The time of each phase depends on each landfill site. Gas production might last longer, for example, if greater amounts of organics are presented in the waste, such as at a landfill receiving higher than average amounts of domestic animal waste. It should be noted that the rate and volume of landfill gas produced at a specific site depending on the characteristics of the waste and some surrounding factors such as the presence of oxygen in the landfill, moisture content, temperature, and waste composition, age of refuse, bacteria, and pH. Landfill can be separated into two types; open and closed dumps. Open dumps posed significant environmental and public health hazards because it has no gas control and collection systems. In contrast, gas in a closed landfill is collected and applied for interesting power resources.

## 2.2 Chemical process in Landfill

Anaerobic digestion is a process of microbial degradation of several trophic groups of bacteria. The quality of the generated biogas depends on the process parameters and substrate composition; the biogas is typically composed of 50 – 75% CH<sub>4</sub>, 25 – 50% CO<sub>2</sub> and 1 – 15% of other gases (The Statistics Portal, 2018; Daniel, 1993). The composition of the gas produced changes with each of the four phases of decomposition.

The first phase is hydrolysis or aerobic degradation, in which the aerobic bacteria digest complex organic matter into CO<sub>2</sub> and H<sub>2</sub>O. The second phase is acidification or anaerobic phase, in which the soluble organic components are decomposed into CO<sub>2</sub>, H<sub>2</sub>, NH<sub>3</sub> and organic acids in the presence of facultative bacteria. The third phase is acetogenesis or initial methanogenic phase which the organic acids produced during the second phase get converted into acetic acid, formic acid, alcohols, H<sub>2</sub> and CO<sub>2</sub> by anaerobic bacteria. In the final phase methanogenesis or stable methanogenic phase, the methanogenic bacteria consume the product of the third phase and produces primarily CH<sub>4</sub>, CO<sub>2</sub>, as well as other trace gases in smaller amount (The Statistics Portal, 2018; Daniel, 1993). Gas flow can be explained by the percentage of gas composition as Figure 2.1 which describes four phases in the landfill.

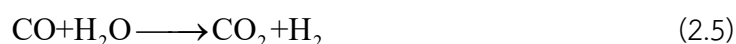


Equations (2.1) – (2.3) is an example of digestion in the landfill. The digestion of acetic acid leads to methane and carbon dioxide whereas ethanol reacts with carbon dioxide to produce methane and acetic acid. Moreover, the productions of the chemical reaction between carbon dioxide and hydrogen are methane and water.

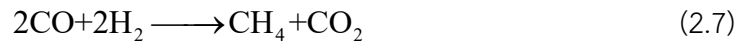
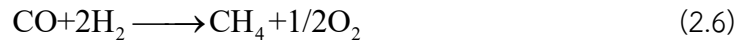
In this research, we divide into two main sections. The first section is the modeling of landfill gas generation which is consideration of methane emissions. In another section, we summarize simulations of landfill gas through the mathematical and genetic algorithms for forecasting. Moreover, we also summarize the use of each model and comparison by previous researches.

Besides experimental and empirical research approach to study the landfill system, mathematical modeling is one of the alternative tools to uncover this complex system problem (Scharff and Jacobs, 2006; Kumar and Samadder, 2017). The mathematical model is a representation in mathematical terms of the behavior of real-world systems or objects. Mathematical models are quick and easy to produce; it can simplify a more complex situation which can help us improve our understanding of the real world as certain variables. Moreover, it enables predictions to be made or can help provide control (Johari et al., 2012; Noor et al., 2013; Scarlet et al., 2015). It can take many forms, such as dynamical systems, statistical models, or differential equations (Feng and Zheng, 2015). Using the systems of ODE is one of the very well-known methods (Feng et al., 2015). In the system of differential equation model, the most important consideration is equilibrium or steady state. Besides, the analysis of the system parameters influencing the system dynamics or behaviors is also a common consideration.

Starting with the full chemical processes of greenhouse gases, we then simply them and reorganize with imposed assumptions to get the final chemical reactions of interest. Firstly, the productions of reactions involving oxygen, hydrogen, water, carbon monoxide, carbon dioxide and methane which can be defined as six equations are written as follows (Bian et al., 2018).



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Here we focus on a closed system that has not to supplement any other gas into the system. We focus on the variation of greenhouse gas,  $\text{CO}_2$  and  $\text{CH}_4$ , chemical reactions of gas generation. As mentioned in phase I, oxygen and nitrogen can be found. So, we consider specific reactions, equations (2.5) and (2.9) which can explain carbon monoxide, water, carbon dioxide, hydrogen, and methane. Next, let  $k_1$  and  $k_2$  be the reaction rates of equation (2.5) and (2.9), respectively. With some manipulation, it gives equations (2.10) - (2.11) to represent the close landfill system where surrounding factors are not considered.



Here, the reaction equation (2.10) represents the dynamics covering from the beginning of phase I and reaching a peak at phase II. After that, equation (2.11) takes over since the starting time of phase III and continues to the last phase IV.

### 2.3 Genetic Algorithm

Optimization is the process of making something better. An engineer or scientist conjures up a new idea and optimization improves on that idea. Optimization consists of trying variations on an initial concept and using the information gained to improve on the idea. A computer is a perfect tool for optimization as long as the idea of variable influencing the idea can be input in electronic format.

Genetic algorithms (GAs) are numerical optimization algorithms inspired by both natural selection and natural genetics. The method is a general one, capable of being applied to an extremely wide range of problems of significant complexity. The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that are based on natural selection, the process that drives biological evolution as a theory of Charles Darwin and Gregor Mendel (Figure 2.2 – 2.4). Charles Darwin stated the theory of natural evolution in the origin of species. Over several generations, biological organisms evolve based on the principle of natural selection “survival of the fittest” to

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reach certain remarkable tasks (David, 1999; Mitchell, 1999; Randy and Sue, 2004; Sivanandam and Deepa, 2008).

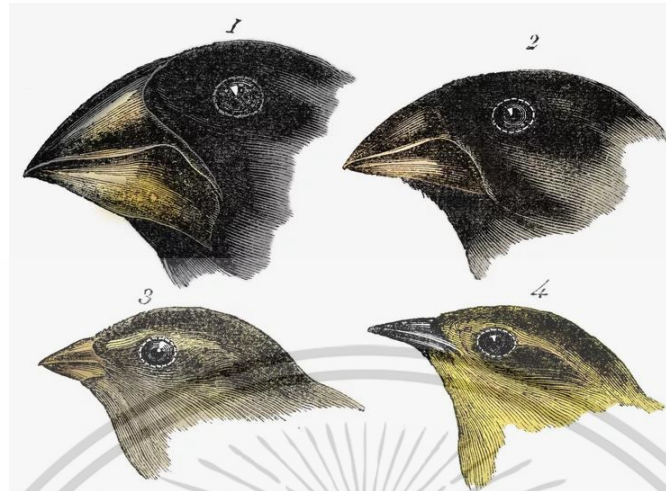


Figure 2.2 Theory of Charles Darwin

(<https://unbound.com/books/why-did-the-policeman-cross-the-road/updates/the-case-of-the-creeping-fox-terrier-clone>)

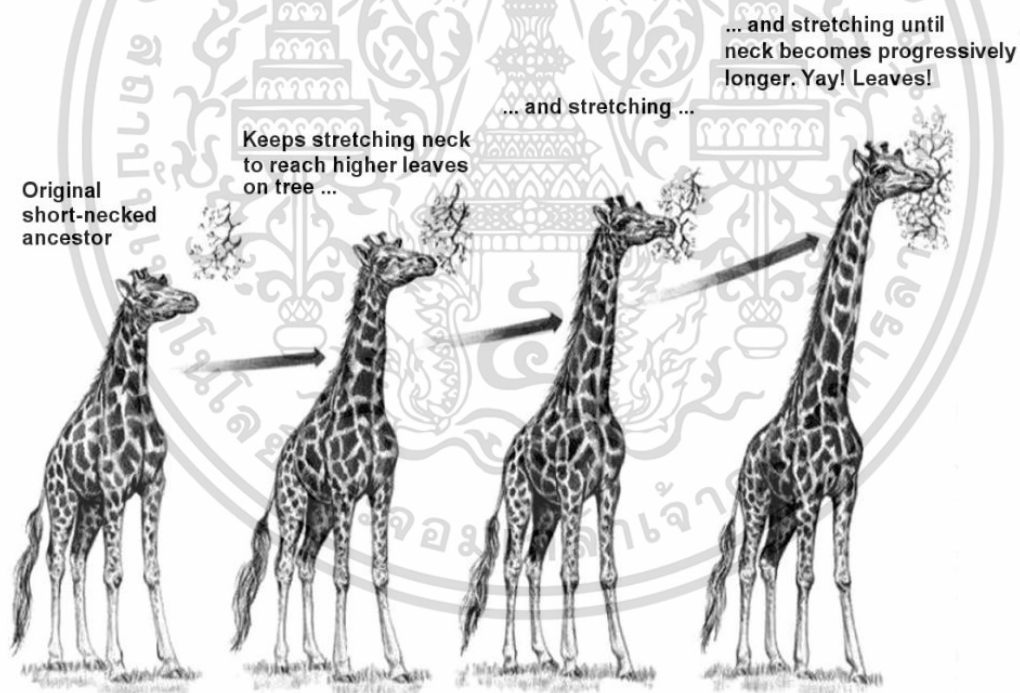


Figure 2.3 Theory of Charles Darwin (Lamarck's Giraffe)

(<https://unbound.com/books/why-did-the-policeman-cross-the-road/updates/the-case-of-the-creeping-fox-terrier-clone>)

Mendel used the common edible pea and started his experiments in 1856. After initial experiments with pea plants, Mendel settled on studying seven traits that seemed to be inherited independently of other traits: seed shape, flower color, seed coat tint, pod  
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shape, unripe pod color, flower location, and plant height. He first focused on seed shape, which was either angular or round. Between 1856 and 1863 Mendel cultivated and tested some 28,000 plants, the majority of which were pea plants. This study showed that when true-breeding different varieties were crossed to each other (e.g., tall plants fertilized by short plants) as Figure 2.4, in the second generation, one in four pea plants had purebred recessive traits, two out of four were hybrids, and one out of four were purebred dominant. His experiments led him to make two generalizations, the Law of Segregation and the Law of Independent Assortment, which later came to be known as Mendel's Laws of Inheritance (David, 1999; Mitchell, 1999; Randy and Sue, 2004; Sivanandam and Deepa, 2008).

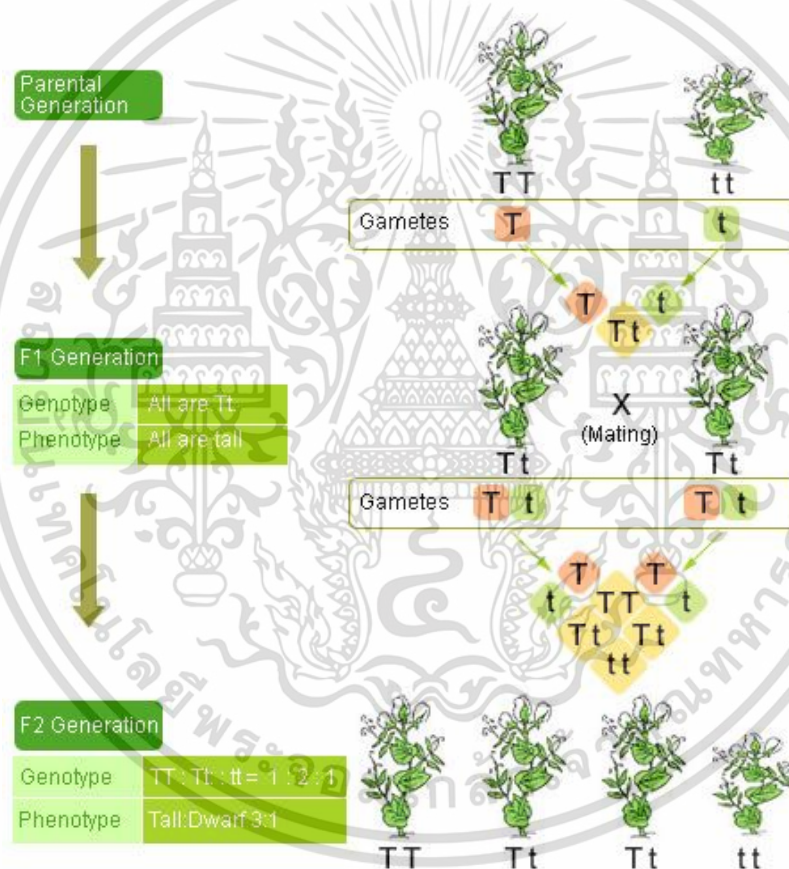


Figure 2.4 Theory of Gregor Mendel

([https://kapitaennem0.wordpress.com/2013/07/17/genetic-algorithm/#\\_ftnref9](https://kapitaennem0.wordpress.com/2013/07/17/genetic-algorithm/#_ftnref9))

The algorithms are simple to understand and the required computer code easy to write. Although there is a growing number of disciples of GAs, the technique has never attracted the attention that, for example, artificial neural networks have. In 1975, Holland developed this idea in his book “Adaptation in natural and artificial systems”. He described how to apply the principles of natural evolution to optimization problems and built the first

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Genetic Algorithms. Holland's theory has been further developed and now GAs stand up as a powerful tool for solving search and optimization problems. Genetic algorithms are based on the principle of genetics and evolution. The power of mathematics lies in technology transfer: there exist certain models and methods, which describe many different phenomena and solve a wide variety of problems. GAs are an example of mathematical technology transfer: by simulating evolution one can solve optimization problems from a variety of sources. Today, GAs are used to resolve complicated optimization problems, like, timetabling, job-shop scheduling, games playing (David, 1999; Mitchell, 1999; Randy and Sue, 2004; Sivanandam and Deepa, 2008).

“Evolution strategies”. This idea was then developed by other researches. GAs was invented by John Holland and developed this idea in his book “Adaptation in natural and artificial systems” in the year 1975. Holland proposed GA as a heuristic method based on “Survival of the fittest”. GA was discovered as a useful tool for search and optimization problems.

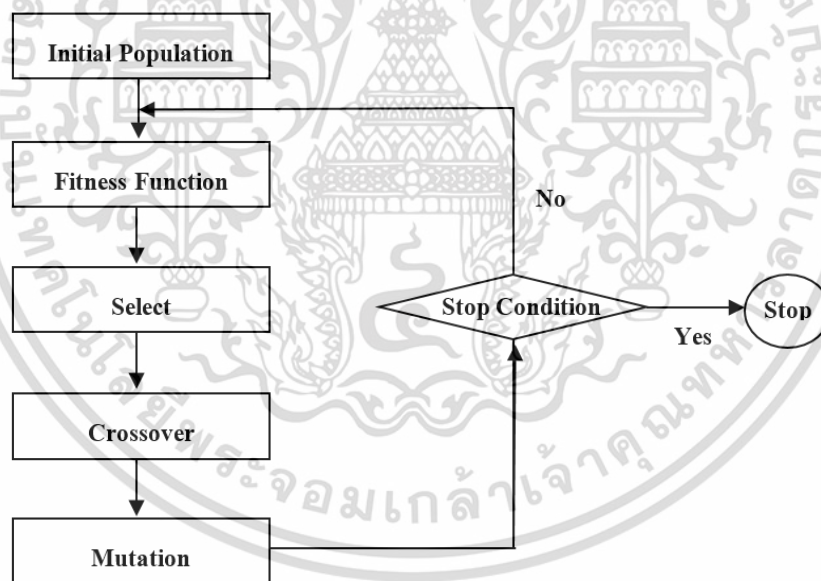


Figure 2.5 The flowchart of the genetic algorithm. (David, 1999)

GAs was in essence invented by John Holland in the 1960s. His reasons for developing such algorithms went far beyond the type of problem-solving with which this text is concerned.

Rather than starting from a single point (or guess) within the search space, GAs are initialized with a population of guesses. These are usually random and will be spread  
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throughout the search space. A typical algorithm then uses three operators, selection, crossover and mutation (chosen in part by analogy with the natural world) to direct the population (over a series of time steps or generations) towards convergence at the global optimum (see Figure 2.5).

Typically, these initial guesses are held as binary encodings (or strings) of the true variables, although increasing the number of GAs use "real-valued" (i.e. base-10) encodings, or encodings that have been chosen to mimic in some manner the natural data structure of the problem. This initial population is then processed by the three main operators.

Selection attempts to apply pressure upon the population like that of natural selection found in biological systems. Poorer performing individuals are weeded out and better performing, or fitter, individuals have a greater than average chance of promoting the information they contain within the next generation.

Crossover allows solutions to exchange information in a way similar to that used by a natural organism undergoing sexual reproduction. One method (termed single-point crossover) is to choose pairs of individuals promoted by the selection operator, randomly choose a single locus (point) within the binary strings and swap all the information (digits) to the right of this locus between the two individuals.

The mutation is used to randomly change (flip) the value of single bits within the individual's strings. It is typically used very sparingly. After selection, crossover and mutation have been applied to the initial population, a new population will have been formed and the generational counter is increased by one. This process of selection, crossover, and mutation is continued until a fixed number of generations have elapsed or some form of convergence criterion has been met.

Table 2.1 Comparison of biological and GA terminology.

Biological	GA
Chromosome or genotype	Structure, or string (often binary)
Locus	A particular (bit) position on the string
Phenotype	Parameter set or solution vector (real-valued)

The binary (or other) string can be considered to be a chromosome, and since only the individuals with a single string are considered here, this chromosome is also the genotype. The organism, or phenotype, is then the result produced by the genotype within

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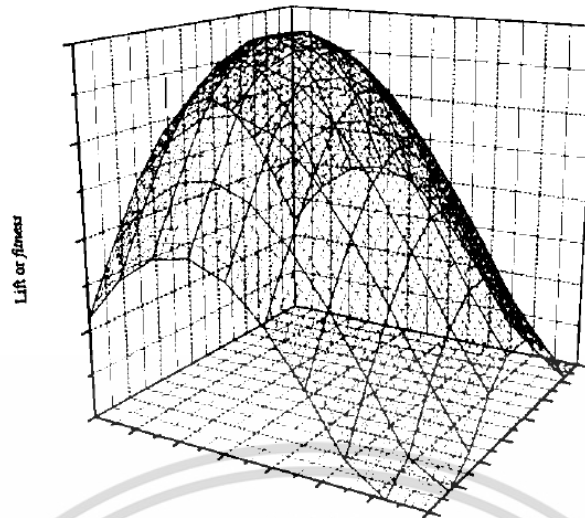
the environment. In gas, this will be a particular set of unknown parameters or an individual solution vector. These correspondences are summarized in Table 2.1.

GAs can be successfully applied among many practical problems and areas as follows:

- Image processing
- Prediction of three-dimensional protein structures
- VLSI (very large scale integration) electronic chip layouts
- Laser technology
- Medicine
- Spacecraft trajectories
- Analysis of time series
- Solid-state physics
- Aeronautics
- Liquid crystals
- Robotics
- Water networks
- Evolving cellular automaton rules
- The architectural aspects of building design
- The automatic evolution of computer software
- Aesthetics
- Jobshop scheduling
- Facial recognition
- Training and designing artificial intelligence systems such as artificial neural Networks
- Control

In a numerical search or optimization problem of possible solutions is being searched to locate the solution that best describes the problem. It is trying to find the best values for a set of adjustable parameters (or variables) that, when included in a mathematical model.

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**Figure 2.6** A simple search space or “fitness landscape” (David, 1999)

Such a plot (Figure 2.6) is a representation of the problem's search space. The concept of a search space is still valid as long as some measure of the distance between solutions can be defined and each solution can be assigned a measure of success, or fitness, within the problem. Better performing, or fitter, solutions will then occupy the peak within the search space (or fitness landscape) and poorer solutions to the valleys.

Such spaces or landscapes can be of surprisingly complex topography. Even for simple problems, there can be numerous peaks of varying heights, separated from each other by valleys on all scales. The highest peak is usually referred to as the global maximum or global optimum, the lesser peaks as local maxima or local optima.

Consider the experimental data shown in Figure 2.7, where measurements of a dependent variable  $y$  have been made at various points  $j$  of the independent variable  $x$  clearly, there is some evidence that  $x$  and  $y$  might be related through:

$$y_j = mx_j + c \quad (2.12)$$

where  $m$  and  $c$  are adjustable parameters

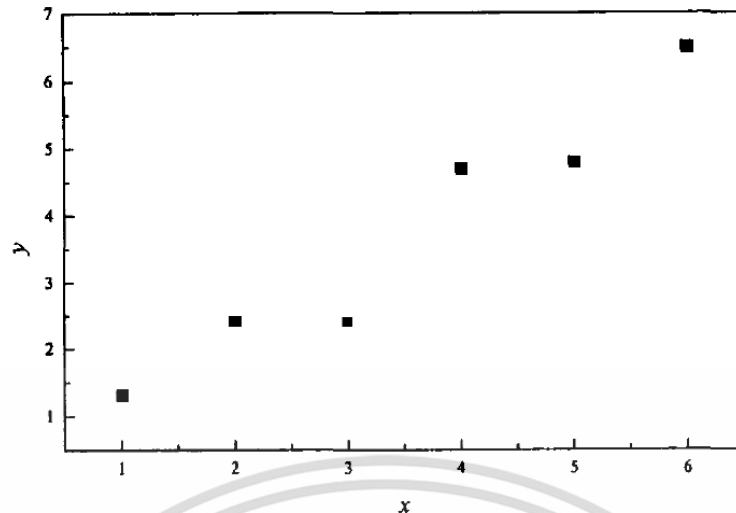


Figure 2.7 Some simple experimental data possible related by  $y = mx + c$  (David, 1999)

One way of then finding  $m$  is simply to use a ruler and estimate the best line through the points by eye. The value of  $m$  is then given by the slope of the line. However, there are more accurate approaches. A common numerical way of finding the best estimate of  $m$  is by use of least-squares estimation. In this technique, the error between that  $y$  predicted using equation (2.12) and that measured during the experiment,  $y$ , is characterized by the objective function. So, (in this case the least-squares cost function) given by,

$$\Omega = \sum_{j=1}^n (\bar{y}_j - y_j)^2 \quad (2.13)$$

where  $n$  is the number of data points. Expanding equation (2.13) gives:

$$\Omega = \sum_{j=1}^n (\bar{y}_j - (mx_j + c))^2 \quad (2.14)$$

As  $c = 0$ ,

$$\Omega = \sum_{j=1}^n (\bar{y}_j - mx_j)^2 \quad (2.15)$$

In essence, the method simply calculates the sum of the squares of the vertical distances between measured values of  $y$  and those predicted by equation (2.12) (see Figure 2.8).  $\Omega$  will be at a minimum when these distances sum to a minimum. The value of  $m$  which gives this value is then the best estimate of  $m$ . This still leaves the problem of finding the lowest value of  $\Omega$ . One way to do this is to use a computer to calculate  $\Omega$  over a fine grid of values of  $m$ , Then simply choose the  $m$  which generates the lowest value of  $\Omega$ . This approach was used together with the data of Figure 2.7 to produce a visualization of

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the problem's search space. It is clear that it is  $m=0.9$ , the better choice as the sum of distances will generate a lesser value of  $\Omega$  as Figure 2.8.

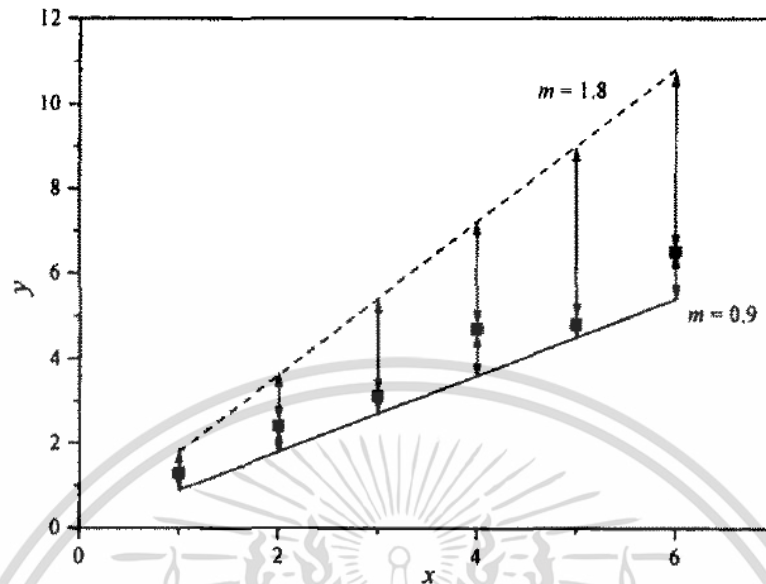


Figure 2.8 Calculate  $\Omega$  for two values of  $m$ ; 0.9 and 1.8 (David, 1999)

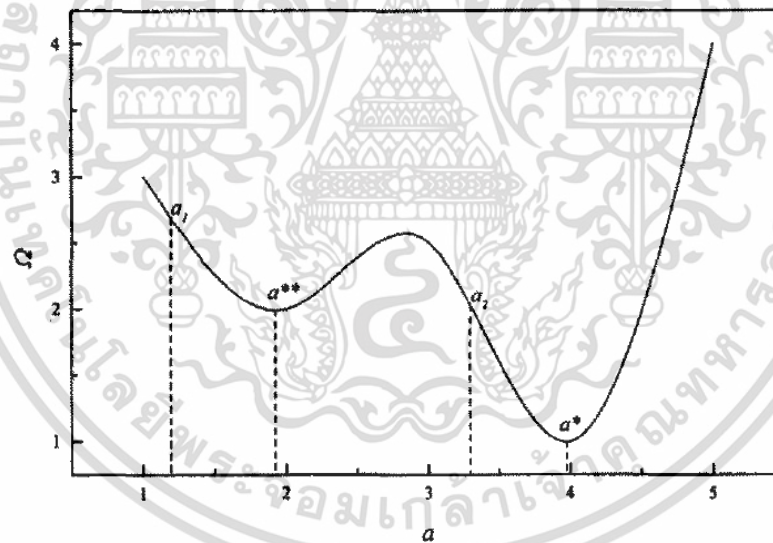


Figure 2.9 A more complex one-dimensional search space with both a global and a local minimum (David, 1999)

This approach, of estimating an unknown parameter, or parameters, by simply solving the problem for a very large number of values of the unknowns is called an enumerative search. It is only really useful if there are relatively few unknown parameters and one can estimate  $\Omega$  rapidly.

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This highlights a serious problem. If the results produced by a search algorithm depend on the starting point, then there will be little confidence in the answers generated. In the case illustrated, one way around this problem would be to start the problem from a series of points and then assume that the true global minimum lies at the lowest minimum identified. This is a frequently adopted strategy. Unfortunately, Figure 2.9 represents a very simple search space. Some of the most successful and robust have proved to be random searches directed by analogies with natural selection and natural genetics--genetic algorithms (David, 1999; Mitchell, 1999; Randy and Sue, 2004; Sivanandam and Deepa, 2008).

### Step of Genetic Algorithm

Given a clearly defined problem to be solved and a bit string representation for candidate solutions, a simple GA works as follows:

1. Start with a randomly generated population of  $n$ -bit chromosomes (candidate solutions to a problem).
2. Calculate the fitness  $f(x)$  of each chromosome  $x$  in the populations.
3. Repeat the following steps until  $n$  offspring have been created:
  - a. Select a pair of parent chromosomes from the current population, the probability of selection being an increasing function of fitness. Selection is done "with replacement," meaning that the same chromosome can be selected more than once to become a parent.
  - b. With probability  $p_c$  (the "crossover probability" or "crossover rate", cross over the pair at a randomly chosen point (chosen with uniform probability) to form two offspring. If no crossover takes place, form two offspring that are exact copies of their respective parents.

Note that here the crossover rate is defined to be the probability that two parents will cross over in a single point. There are also "multipoint crossover" versions of the GA in which the crossover rate for a pair of parents is the number of points at which a crossover takes place.)

  - c. Mutate the two offspring at each locus with probability  $p_m$  (the mutation probability or mutation rate), and place the resulting chromosomes in the new population. If  $n$  is odd, one new population member can be discarded at random.
4. Replace the current population with the new population.
5. Go to step 2.

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## 2.4 Runge–Kutta Method

Numerical approximations for initial value problems (IVPs) comes under the general classification of Runge–Kutta (RK) methods. The derivation is based on the question of whether it is possible to determine an explicit method for finding  $y_{n+1}$  and has a predetermined truncation error.

If the differential equation is

$$\frac{dy}{dx} = f(x, y), \quad (2.16)$$

the step from  $x_n$  to  $x_{n+1} = x_n + h$  is made by the formulas

$$y_{n+1} = y_n + (k_1 + 2k_2 + 2k_3 + k_4)/6, \quad (2.17)$$

where

$$\begin{aligned} k_1 &= hf(x_n, y_n), \\ k_2 &= hf\left(x_n + \frac{1}{2}h, y_n + \frac{1}{2}k_1\right), \\ k_3 &= hf\left(x_n + \frac{1}{2}h, y_n + \frac{1}{2}k_2\right), \\ k_4 &= hf(x_n + h, y_n + k_3), \end{aligned}$$

## 2.5 Literature reviews

Nowadays, there are many kinds of research on the model for landfill. In this part, we collect and explain the model on landfill gas including techniques to find a solution for each condition. Landfill models can be divided into many fields such as mathematical model which use the mathematical and numerical technique to show results. Computer simulation is another technique widely uses to describe landfill gas and transition.

### 2.5.1 Estimation of methane generation in landfill

The most research on landfills studies about landfill gas emission especially methane since it is over 20 – times global warming potential. Some research summarizes the model to estimate methane emission from the landfills. To estimate the landfill gas generation, เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้งานเพื่อการศึกษาเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า ไม่ว่าจะกรณีใดๆ ทั้งสิ้น อีกทั้งห้ามมิให้ดัดแปลงเนื้อหา และต้องอ้างอิงถึงเจ้าของเอกสารทุกครั้งที่มีการนำไปใช้

several studies have investigated and compared. Some of the most widely used models are described in Table 2.2 (Noor et al., 2013; Scarlat et al., 2015; Johari et al., 2012; Kumar and Samadder, 2017; Feng and Zheng, 2015). Most models based on first-order decay (Monod first-order kinetic) model which is a linear relationship of the maximum gas generation potential per waste weight unit as well as an exponential relationship of the waste degradation rate and time. Whereas that zero-order model gives significant inaccurate outcomes (Noor et al., 2013).

Any models were modified for a specific area in which the clear reference is assignment and source of parameters. First-order decay (FOD) for different climate conditions, parameter  $k$  and  $L_0$  different by technique. Sometimes it provides for regression analysis, curve fitting or precipitation-based empirical model. Moreover, it depends on waste composition or experimental work (Scarlat et al., 2015). It leads to results fitted well to the actual data or outputs underestimated methane generation. Therefore, the determination of parameters affects results accuracy. The outputs of four mathematical models (TNO, Afvalzorg, LandGEM and EPER Germany), for example, diverse from each other with increasing time (Johari et al., 2012). The advantages and disadvantages, including the assumption of 13 models (IPCC, EPER Germany, SWANA zero-order, SWANA first order, LandGEM, TNO, GasSim, EPER France, Afvalzorg, LFGGEN, Mexico, Halvadakis and Numerical models) provide to summarize the differences of each other (Scarlat et al., 2015). Table 2.2 shows examples of the estimation of methane generation in the landfill.

Landfill gas generation rates are currently estimated by mathematical models which depend on each input parameter for each model. Among the model widely used are TNO, Afvalzorg, LandGEM, EPER Germany, and IPCC which formulas are shown in Table 2.2 The first three models are the first-order model whereas the last two models are zero-order models. TNO-model use parameters based on real data of landfill gas generation. The model exists as a formula. Afvalzorg is also a first-order multiphase model that looks similar to TNO-model expect the conversion factor. This model based on waste characteristics in Netherlands and waste is classified into three categories in terms of degradation rate. Besides, it is a freeware model. LandGEM is a model based on waste composition in the US. It is confusing and complicated mathematics. For the model, namely EPER Germany, consider the proportion of degradable carbon and waste amount while IPCC is model based on degradable organic carbon and waste disposed which accommodates four different climate regions (Renou et al., 2008; Noor et al., 2013; Scarlat et al., 2015; Johari et al., 2012;

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Kumar and Samadder, 2017; Feng and Zheng, 2015; Feng et al., 2015; Bian et al.,2018; Hu et al., 2012).



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Table 2.2 Methane emission models.

Model name	Formula	Model description	Advantages	Disadvantages
TNO	$\alpha_t = \zeta \times 1.87 \times A \times C_0 \times k_1 \times e^{-k_1 t}$ <p>where</p> <p><math>\alpha_t</math> = landfill gas production at a given time (<math>\text{m}^3 \cdot \text{year}^{-1}</math>)</p> <p><math>\zeta</math> = dissimilation factor, 0.58</p> <p>1.87 = conversion factor (<math>\text{m}^3</math>)</p> <p><math>A</math> = amount of waste in place (Mg)</p> <p><math>C_0</math> = amount of organic carbon in waste (<math>\text{kgC Mg Waste}^{-1}</math>)</p> <p><math>k_1</math> = degradation rate constant, 0.094 (<math>\text{year}^{-1}</math>)</p> <p><math>t</math> = time elapsed since depositing (<math>\text{year}^{-1}</math>)</p>	First-order model which parameters based on real data of landfill gas generation in Netherlands.	Direct estimation of methane and landfill gas.	Information on organic components of waste is not available.
Afvalzorg	$\alpha_t = \zeta \times \sum_{i=1}^3 c \times A \times C_0 \times k_{1,i} \times e^{-k_{1,i} t}$ <p>where</p> <p><math>\alpha_t</math> = landfill gas production at a given time (<math>\text{m}^3 \cdot \text{year}^{-1}</math>)</p> <p><math>\zeta</math> = dissimilation factor</p> <p><math>i</math> = waste fraction with degradation rate <math>k_{1,i}</math></p> <p><math>c</math> = conversion factor (<math>\text{m}^3 \cdot \text{kg}^{-1}</math>)</p> <p><math>A</math> = amount of waste (tonne)</p> <p><math>C_0</math> = amount of organic matter (<math>\text{kg} \cdot \text{tonne}^{-1}</math>)</p> <p><math>k_{1,i}</math> = degradation rate constant of fraction <math>i</math> (<math>\text{year}^{-1}</math>)</p> <p><math>t</math> = time elapsed since depositing (year)</p>	First-order, multi-phase model based on the waste characteristics in Netherlands. Waste is classified into three categories in terms of the degradation rate.	Freeware model which available on demand.	Organic matter or carbon content data were not available for all waste categories.

Table 2.2 Methane emission models (Cont.)

Model name	Formula	Model description	Advantages	Disadvantages
LandGEM	$Q_{CH_4} = \sum_{i=1}^n k \times L_0 \times M_i \times e^{-k \cdot t_i}$ <p>where</p> <p><math>Q_{CH_4}</math> = methane emission rate [<math>m^3 CH_4 \text{ year}^{-1}</math>]</p> <p><math>k</math> = methane generation constant [<math>\text{year}^{-1}</math>]</p> <p><math>L_0</math> = methane generation potential [<math>m^3 CH_4 \text{ Mg Waste}^{-1}</math>]</p> <p><math>M_i</math> = mass of waste in <math>i^{\text{th}}</math> section [Mg]</p> <p><math>t_i</math> = age of the <math>i^{\text{th}}</math> increment or section [year]</p>	<p>First-order model based on waste composition in the US. This model uses a first-order decay rate equation to calculate landfill gas generation.</p>	<p>User-friendly in a spreadsheet environment.</p>	<p>Inaccurate assumptions about some variables can result in large errors.</p>
EPER Germany	$FE_{CH_4} = \sum_x FE_0 \times \left( \sum_{i=1}^3 A_i \times p_i \times k_i \times e^{k_i t} \right)$ <p>where</p> <p><math>FE_{CH_4}</math> = annual methane production (<math>m^3 \cdot \text{year}^{-1}</math>)</p> <p><math>FE_0</math> = methane generation potential (<math>m^3 \cdot \text{tonne}^{-1}</math>)</p> <p><math>A_i</math> = normalization factor</p> <p><math>p_i</math> = waste fraction with degradation rate <math>k_i</math></p> <p><math>k_i</math> = degradation rate of fraction <math>i</math> (<math>\text{year}^{-1}</math>)</p> <p><math>t</math> = age of waste (year)</p>	<p>Zero-order model based on amount of waste and proportion of biodegradable carbon. It is basically used in Germany.</p>	<p>The estimates independent of the amount of biogas already generated. This model is useful for the estimation of large fluctuations.</p>	<p>Confusing and complicated mathematics. The estimation is not closed landfill sites. It is only roughly predicted under operation.</p>

Table 2.2 Methane emission models (Cont.)

Model name	Formula	Model description	Advantages	Disadvantages
IPCC	$Q = \left[ \sum_{x=S}^{T-1} \left\{ MSWT_x \times MSWF_x \times L_0 \left( e^{-k(T-x-1)} - e^{-k(T-x)} \right) \right\} - R \right] \times (1 - OX)$ <p>where</p> <p><math>L_0</math> = methane generation potential (Gg of waste) = <math>1.33 \times F \times DOC \times DOC_F</math></p> <p><math>F</math> = fraction by volume of CH<sub>4</sub> in landfill gas</p> <p><math>DOC</math> = amount of degradable organic carbon</p> <p><math>DOC_F</math> = fraction of DOC decomposes</p> <p><math>Q</math> = methane emissions (Gg · year<sup>-1</sup>)</p> <p><math>MSWT</math> = total MSW generated (Gg · year<sup>-1</sup>)</p> <p><math>MSWF</math> = fraction of MSW landfilled</p> <p><math>k</math> = reaction constant (year<sup>-1</sup>)</p> <p><math>T</math> = inventory year for which emissions are calculated</p> <p><math>x</math> = year in which waste was landfilled</p> <p><math>S</math> = start year of inventory calculation</p> <p><math>R</math> = recovered methane (Gg · year<sup>-1</sup>)</p> <p><math>OX</math> = oxidation factor (fraction)</p>	Zero order model based on organic carbon and waste disposal. It was developed for the European countries.	Accommodates to four different climate regions.	Equations are quietly complicated and required many parameters.

## 2.5.2 Computer simulations of landfill gas

Many kinds of research study computer simulations based on mathematical models of landfill gas. The interesting research is a series of “Computer simulation of gas generation and transport in landfills”. Firstly, the model entitles “Quasi-steady-state condition” which is a three dimensional model for a four-component gas mixture, takes into account the effect of heterogeneity in the distributions of the permeability and porosity in the landfill. Non-linear equations of mass transport and reaction are solved by a novel iterative method (Hashemi et al., 2002). Secondly, it is considered on dynamic conditions by biodegradation of wastes and transportation. The model is utilized for investigating the dynamic behavior of a landfill, and in particular pressure build-up, under a variety of conditions. Besides, a comparison of the model’s predictions with experimental data for a particular landfill indicates the potential of the model for predicting the dynamic behavior of large landfills (Sanchez et al., 2006). Thirdly, development of landfills’ optimal model, this problem is addressed by formulating it as one of optimization, whereby the optimal spatial distributions of the porosity, permeability, tortuosity factor, and the total potential of various types of wastes for producing the gases in a landfill are determined, given some limited experimental data for a property of the landfill, such as the amount of methane which is extracted from it over a period of time. The numerical simulator is coupled to the Genetic algorithm to optimize the parameter space that characterizes the landfill’s morphology and the reactive properties of the wastes (Sanchez et al., 2007).

The fourth model entitles “Modeling of liquid–gas flow” which based on a general model of biodegradation (Richardson equation). It demonstrates the strong effect of the heterogeneities of landfill represented by the spatial distribution of the local porosities, as well as an anisotropic distribution of the local permeability on the behavior of a landfill, and pressure buildup in it (Sanchez et al., 2010). The next model, namely “Use of artificial neural network and the genetic algorithm for short- and long- term forecasting and planning”. This model develops an artificial neural network (ANN) to make accurate short-term predictions for several important quantities in a large landfill, including the temperature and gas concentrations ( $\text{CH}_4$ ,  $\text{CO}_2$ , and  $\text{O}_2$ ) (Li et al., 2011). The last model, dynamic updating of the model using the ensemble Kalman filter, based on a combination of the genetic algorithm (GA) and the ensemble Kalman filter (EnKF) to generate and update the landfill model (Li et al., 2011).

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al., 2012). All models were developed for each condition that the updated models are complex and use higher techniques as Table 2.3.

Next, other research that interested in landfill gas model simulation. Feng (2015) presents a two – dimensional gas flow model to predict the distribution of gas pressure, the CH<sub>4</sub> emission flux through partial differential equation with analytical and numerical solutions. This model is indicative of the flow towards a combined extraction system of vertical wells and horizontal gravel-filled trenches. Moreover, the model has a horizontal layered structure to accommodate anisotropy of municipal solid waste (MSW) and vertical variations in both gas generation rate and permeability. These results provide helpful guidelines to landfill engineers in designing a LFG control system. It can be used to properly describe the gas flow towards a combined extraction system of vertical wells and horizontal drains in landfills (Feng and Zheng, 2015a). In the same year, they improve their work by developing the previous model for the different conditions to enable the study of the gas pressure distribution, well pressure and recovery efficiency in layered landfills with horizontal wells. A horizontal layered structure is used to accommodate the non-homogeneity of various municipal solid waste aspects concerning depth, including gas generation, permeability, and temperature. The solution was verified against another analytical solution and numerical simulation. Moreover, a sensitivity analysis of single-well model parameters is performed to optimize a double-well system. The results show that a landfill with horizontal collection systems cannot be assumed to be one dimensional with increasing well spacing (Feng et al., 2015b).

A comparative analysis, throughout mathematical modeling and simulation, of different methanol production routes, by considering four biogas sources: landfill, palm oil effluent, corn cobs, and sorghum fermentation. For all cases, an optimization study was performed, to maximize the methanol production. The results evidenced that the biogas from palm oil showed to be the most profitable concerning the other sources. On the other hand, the landfill gas showed to be a very limited capacity for methanol supply. Finally, process optimization indicates that the operating conditions must be adjusted concerning the biogas composition, to allow the maximum production (Santos et al., 2018).

A model that estimates methane emissions using ambient air methane measurements obtained on the surface of a landfill. The method is Genetic Algorithms

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based optimization combined with the standard Gaussian dispersion model is employed to identify locations as well as emission rates of potential emission sources throughout a municipal solid waste landfill. Four case studies are employed to evaluate the performance of the proposed methodology. Results of the four case studies showed the importance of having an overall coverage of all waste disposal of the landfill when surface concentration measurements are performed (Kormi et al., 2018).

Talaiekhosani et al. (2018) show dispersion modeling by using the AERMOD View model which is an atmospheric dispersion modeling system is an integrated system that includes three modules. Firstly, a steady-state dispersion model designed for short-range (up to 50 kilometers) dispersion of air pollutant emissions from sources. Secondly, a meteorological data preprocessor (AERMET) that accepts surface meteorological data, upper air soundings data from on-site instrument towers. It then calculates the atmospheric parameters needed by the dispersion model. Lastly, a terrain preprocessor (AERMAP) whose main purpose is to provide a physical relationship between terrain features and the behavior of air pollution plumes. AERMOD View needs to be provided with several groups of data, such as wind direction, wind speed, ceiling height, global horizontal radiation, and relative humidity, etc. Besides, AERMOD also includes PRIME (Plume Rise Model Enhancements) which is an algorithm for modeling the effects of downwash created by the pollution plume flowing over nearby buildings. The results show dispersion modeling for biogas, methane, carbon dioxide, non-methane organic compounds, and carbon monoxide (Talaiekhosani et al., 2018).

Moreover, a simulation model that combines the multicomponent diffusive equation and Darcy's law with the dual Monod kinetic equation or convection-diffusion model to simulate  $\text{CH}_4$  transport oxidation and emission in landfill cover soils. This model describes  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{O}_2$ , and  $\text{N}_2$ . The results show methane emission rate, methane emission and the relationship of parameters. Additionally, it is a reliable method for the estimation of methane emission from landfill which provides basic data for the creation of a global  $\text{CH}_4$  emission inventory (Bian et al., 2018) as Table 2.4.

**Table 2.3** Summary of research in a series of “Computer simulation of gas generation and transport in landfills”

Authors	Model's Name	Technique	Finding
Hashemi et al. (2002) [40]	Computer simulation of gas generation and transport in landfills I: quasi-steady-state condition	Analytical analysis and numerical computation	The model is utilized for investigating the gas generation and transport in a model landfill, and the effect of various parameters.
Sanchez et al. (2006)	Computer simulation of gas generation and transport in landfills II: Dynamic conditions	Analytical analysis and numerical computation	The comparison of the model's predictions with experimental data indicates the potential of the model for predicting the dynamic behavior of large landfills
Sanchez et al. (2007)	Computer simulation of gas generation and transport in landfills. III: Development of landfills' optimal model	Analytical analysis, numerical simulation and optimization process (genetic algorithms)	The computations are carried out highly efficiently and in a reasonable time, even if one must determine the optimal values of thousands of parameters.
Sanchez et al. (2010)	Computer simulation of gas generation and transport in landfills. IV: Modeling of liquid-gas flow	Analytical analysis and numerical simulation	The results include the flow of leachate and landfill gas.
Li et al. (2011)	Computer simulation of gas generation and transport in landfills. V: Use of artificial neural network and the genetic algorithm for short- and long-term forecasting and planning	Artificial neural network (ANN) and genetic algorithms	The results conclude that this model is a powerful approach for developing realistic models of landfills that can be used for making both short and long term predictions and planning.
Li et al. (2012)	Computer simulation of gas generation and transport in landfills VI: Dynamic updating of the model using the ensemble Kalman filter	Genetic algorithms and sequential Gaussian simulation (Ensemble Kalman Filter: EnKF)	The results demonstrate the effectiveness and applicability of EnKF updating.

**Table 2.4** Summary of other papers on computer simulations about landfill gas

Authors	Model's Name	Technique	Finding
Feng et al. (2015a)	A two-dimensional gas flow model for layered municipal solid waste landfills	Analytical techniques and Eigenfunction expansion	The results provide helpful guidelines to landfill engineers in designing a LFG control system for vertical wells and horizontal drains.
Feng et al. (2015b)	A model for gas pressure in layered landfills with horizontal gas collection systems	Analytical techniques, separation of variable and finite integral transforms	The solution can be used for the verification of more complex models and the preliminary design of a horizontal well system.
Santos et al. (2018)	Simulation and optimization of a methanol synthesis process from different biogas sources	Numerical methods and optimization process	The optimal operating parameters were found similar to the observation. It provides a good alternative to controlling methane greenhouse gas emissions from municipal solid waste.
Kormi et al. (2011)	Estimation of fugitive landfill methane emissions using surface emission monitoring and Genetic Algorithms optimization	Genetic algorithms and standard Gaussian dispersion model	The proposed approach enables the estimation of landfill methane emissions and localization of major emission hotspots in the studied landfills.
Talaiekhazani et al. (2012)	Gaseous emissions of landfill and modeling of their dispersion in the atmosphere of Shahrekord, Iran	LandGEM and AERMOD view software	Results show that modeling of pollutants' distribution into the atmosphere
Bian et al. (2018b)	A Simulation model for estimating methane oxidation and emission from landfill cover soils	Convection - Diffusion model, numerical simulation and sensitivity analysis	The values of methane emissions predicted using the new model fitted well with the values measured through laboratory experiments.

### 2.5.3 Parameter Estimation

Thompson et al. (2009) compare modeled methane generation to methane generation recovery rates for a statistical sample of landfills. The result shows that LandGEM is the least error and TNO is a better model than EPER Germany. It also classifies the case of the parameter (amount of organic carbon in waste) which gives different error and correlation. Vu (2017) also compare CH<sub>4</sub> estimations from landfill gas models with actual data. In particular, LandGEM is the best fit model and Afvalzorg gives a lower percentage error than IPCC for all cases. Moreover, parameters  $k$  and  $L_0$  were changed for each model again. It can be concluding that all landfill does not have to use the same value of parameters. The optimal parameters depend on actual data (Vu et al, 2017).

CH<sub>4</sub> generation variables such as methane generation rate constant ( $k$ ) and generation potential ( $L_0$ ) are important factors for several models. Table 2.5 summarize landfill gas model parameters with different climatic conditions which consist of warm, cold, wet and semi-arid for different landfill locations. Methane generation rate constant and generation potential are determined from many techniques such as regression analysis, curve fitting, waste composition, experimental work, minimizing the RSS, collection determined from measured CH<sub>4</sub>, and precipitation-based empirical model.

**Table 2.5** Landfill gas model parameters with different climatic conditions (Vu et al., 2017).

Reference	Landfill location	Models	k (year <sup>-1</sup> )	L <sub>0</sub> (m <sup>3</sup> /Mg)	k determined from	L <sub>0</sub> determined from	Findings/Remarks
<b>Warm</b>							
Faour et al. (2007)	CSWMC, SSWMC and Landfill A, US	LandGEM	0.11–0.21	87–115	Regression analysis	Regression analysis	LandGEM results fitted well to the actual data.
Machado et al. (2009)	Salvador, Brazil	FOD USEPA 1996 and IPCC	0.2–0.21	65.9–66.6	Curve fitting	Curve fitting	L <sub>0</sub> were lower than those normally presented in the literature for developing tropical countries.
Bella et al. (2011)	Palermo, Italy	LandGEM, Ehrlic	0.04	100	Used default values	Used default values	The models slightly overestimated methane generation.
Amini et al. (2013)	Florida, US	LandGEM	0.040–0.090	74–140	Curve fitting and linear regression	Waste composition	LandGEM underestimated methane generation.
Amini et al. (2012)	Florida, US	LandGEM	0.040–0.130	56–77	Curve fitting and linear regression	Waste composition	LandGEM underestimated methane generation.
Govindan and Agamuthu (2014)	Malaysia	IPCC	0.08; 0.09	0.08; 0.12 (DOC)	Precipitation-based empirical model	Waste composition	Overestimated CH <sub>4</sub> generation at default k and DOC values. Estimated error was reduce by 69% and 81% at calculated k and DOC values
<b>Cold, wet</b>							
Wang et al. (2013, 2015)	US	LandGEM	0.09–0.12	55–100	k was the value determined by minimizing the RSS	L <sub>0</sub> values given in the legend	Optimal k was higher than the default AP-42
Tolaymat et al. (2010)	US	LandGEM	0.06	48	determined from measured CH <sub>4</sub> collection	Aged defined waste samples	Optimal k was slightly higher than the default AP-42
Thompson et al. (2009)	Ontario, Canada	EPER, TNO, Belgium,	0.037	137	Precipitation-based empirical model	Waste composition	All the models overestimated methane generation except for LandGEM.
	Quebec, Canada	LandGEM, Scholl Canyon	0.042	195			
Ishii and Furuichi (2013)	Hokkaido, Japan	FOD	0.062 (food)	214.4 (food)	Curve-fitted lines using FOD	Aged defined waste samples	k of food waste was smaller than that of the IPCC due to the lower temperature
Mou et al. (2015a,b)	Denmark	Afvalzorg, IPCC, LandGEM	0.013–0.19	8–107	Experimental work	Waste composition	All three models overestimated at default k and L <sub>0</sub> values. Afvalzorg fitted well at specific k and L <sub>0</sub> values for the landfills
<b>Cold, semi-arid</b>							
Thompson et al. (2009)	Alberta, Canada	EPER, TNO, Belgium, LandGEM, Scholl Canyon	0.023	152	Precipitation-based empirical model	Waste composition	All the models overestimated methane generation except for the LandGEM.
Thompson et al. (2009)	Regina, Saskatoon	N/A	0.023	N/A	Precipitation-based empirical model	N/A	N/A
Environment Canada (2015)	Regina, Saskatoon	N/A	0.006–0.011	132	Precipitation-based empirical model	Waste composition	L <sub>0</sub> values derived from the most recent version of the report

## Chapter 3

# Research Methodology

### 3.1 Modeling and Simulation

A “model” is a mathematical, logical, physical, or procedural representation of some real system. A “modeling” is the process of developing a model. A software “simulation” is the implementation of a mathematical model in executable form and the execution of that model over time. Modeling and simulation is a combination of mathematical models and computer software to the wide discipline of creating, analyzing, implementing, and using models and simulations.

Modeling and simulation are representative of physical experimentation in which computers are used to calculate the results of some physical phenomena. Firstly, a computer is used to build a mathematical model that contains all the parameters of the physical model and represents physical model in a virtual form then conditions are applied. In the simulation, actual experimentation can be avoided which is costly and time-consuming instead of using mathematical knowledge and computer computation power to solve real-world problems cheaply and in a time-efficient manner. Modeling and simulation can facilitate understanding of a system's behavior without actually testing the system in the real world. Besides, simulation can support experimentation that occurs totally in software, or in human-in-the-loop environments where simulation represents systems or generates data needed to meet experiment objectives. Furthermore, simulation can be used to train persons using a virtual environment that would otherwise be difficult or expensive to produce.

### 3.2 Mathematical model for landfill

To understand the gas system in this close landfill through the mathematical equation, starting from the previous chemical models, we formulate mathematical representation using the system of differential equations describing changes of each gas in this system. Consider chemical reaction (2.10), the change of each chemical species depends on reactants,  $\text{CO}$ , and  $\text{H}_2\text{O}$ , where the reactants

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decline with rate  $k_1$ . In contrast, the products,  $\text{CO}_2$ , and  $\text{H}_2$ , increase with rate  $k_1$ . It can be written as four differential equations as follows.

$$\begin{aligned}\frac{d[\text{CO}]}{dt} &= -k_1[\text{CO}][\text{H}_2\text{O}] \\ \frac{d[\text{H}_2\text{O}]}{dt} &= -k_1[\text{CO}][\text{H}_2\text{O}] \\ \frac{d[\text{CO}_2]}{dt} &= k_1[\text{CO}][\text{H}_2\text{O}] \\ \frac{d[\text{H}_2]}{dt} &= k_1[\text{CO}][\text{H}_2\text{O}]\end{aligned}\quad (3.1)$$

Similarly, the differential equations of the chemical reaction (2.11) are formulated as follows.

$$\begin{aligned}\frac{d[\text{CO}_2]}{dt} &= -k_2[\text{CO}_2][\text{H}_2]^4 \\ \frac{d[\text{H}_2]}{dt} &= -k_2[\text{CO}_2][\text{H}_2]^4 \\ \frac{d[\text{CH}_4]}{dt} &= k_2[\text{CO}_2][\text{H}_2]^4 \\ \frac{d[\text{H}_2\text{O}]}{dt} &= k_2[\text{CO}_2][\text{H}_2]^4\end{aligned}\quad (3.2)$$

For the chemical reaction (2.11), the change of each gas depends on reactants,  $\text{CO}_2$  and  $\text{H}_2$ , decreases with rate  $k_2$  while  $\text{CH}_4$  and  $\text{H}_2\text{O}$  raises with rate  $k_2$ . By equation (3.1) – (3.2), some gas has two differential equations to explain its variation. Therefore, we can conclude that

$$\begin{aligned}\frac{d[\text{CO}]}{dt} &= -k_1[\text{CO}][\text{H}_2\text{O}] \\ \frac{d[\text{H}_2\text{O}]}{dt} &= -k'_1[\text{CO}][\text{H}_2\text{O}] + k'_2[\text{CO}_2][\text{H}_2]^4 \\ \frac{d[\text{CO}_2]}{dt} &= k'_1[\text{CO}][\text{H}_2\text{O}] - k'_2[\text{CO}_2][\text{H}_2]^4 \\ \frac{d[\text{H}_2]}{dt} &= k'_1[\text{CO}][\text{H}_2\text{O}] - k'_2[\text{CO}_2][\text{H}_2]^4 \\ \frac{d[\text{CH}_4]}{dt} &= k_2[\text{CO}_2][\text{H}_2]^4\end{aligned}\quad (3.3)$$

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It is seen that equation (3.3) is nonlinear first-order ODEs. To understand the system dynamic and behavior, we apply numerical methods (fourth-order Runge-Kutta method) to solve for solutions. It should be remarked that for the sake of simplicity we redefine reaction rates  $k_1$ ,  $k_2$ ,  $k'_1 = 0.5k_1$  and  $k'_2 = 0.5k_2$  to be numerically analyzed.



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# Chapter 4

## Main Results and Discussion

### 4.1 Numerical Solution

We applied the Runge – Kutta method via the MATLAB program to offers ode45 to solve the system. Each result it takes a few minutes to get the data from time 0 up to time 300. Since it is very important to validate our model, we then generate the data to see if our numerical data are consistent with those data Is given in Figure 4.1. As mentioned previously, there are four phases in the reaction landfill system. Phase I features the increase in CO<sub>2</sub> from almost null. This phase is the aerobic phase by nature and not included in our model study, meaning we consider the system dynamics from the anaerobic phase (phase II) to Phase IV. Phase II typically provides a more increasing of CO<sub>2</sub> and reaches a peak at the end of this phase which is the starting point of phase III. It continues to the intercession of CO<sub>2</sub> and CH<sub>4</sub> which is time to the terminal of phase III. After that, it transitions to phase IV which shows stable for all gases.

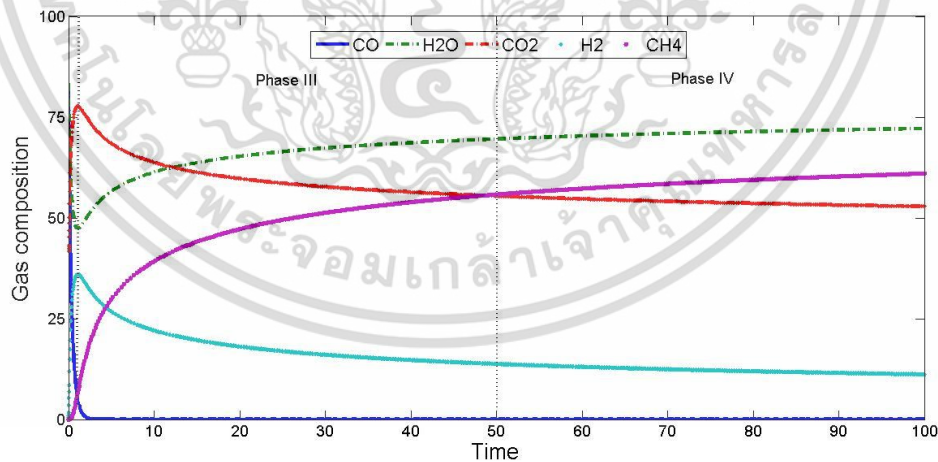


Figure 4.1 Numerical solution of equation 3.3 where  $k_1 = k_2 = 4$  with the time between 0 and 100

Figure 4.1 shows typical solution curves for the case of  $k_1 = k_2 = 4$ . where define initial value for CO, H<sub>2</sub>O, CO<sub>2</sub>, H<sub>2</sub>, and CH<sub>4</sub> as 1, 1, 0.5, 0, and 0 respectively. It เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้งานเพื่อการศึกษาเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า ไม่ว่าจะกรณีใดๆ ทั้งสิ้น อีกทั้งห้ามมิให้ตัดแปลงเนื้อหา และต้องอ้างอิงถึงเจ้าของเอกสารทุกครั้งที่มีการนำไปใช้

at least qualitatively is consistent with those shown in Figure 4.1. Here are solutions that include water and carbon monoxide for the sake of understanding. The data of  $\text{CO}_2$ , and  $\text{H}_2$  have the same trend.  $\text{H}_2$  in this system slowly decreases. Since the data in Figure 4.1 is not well represented what changes in the second phase due to the time scale mismatch, we then extend “magnify” the results between time 0 and 5. As seen in Figure 4.2 it clearly shows the second and third phase which is divided by the peak of carbon dioxide as mentioned before.

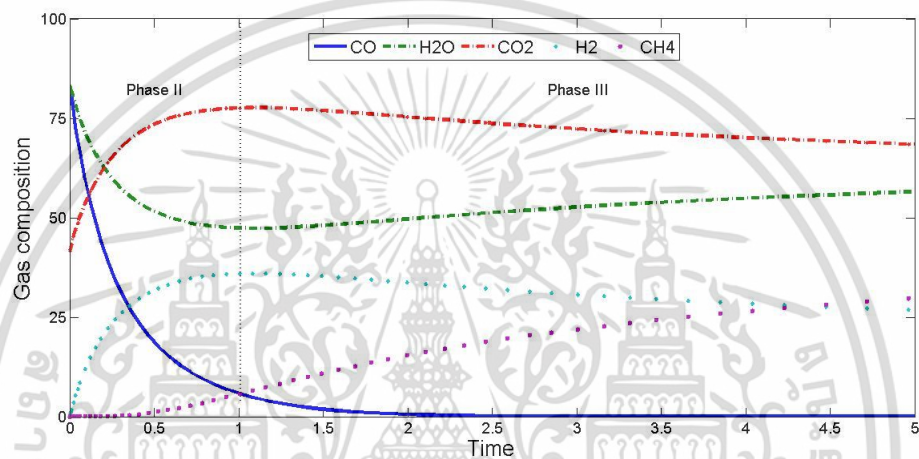


Figure 4.2 Numerical solution of equation 3.3 where  $k_1 = k_2 = 4$  with time between 0 and 5

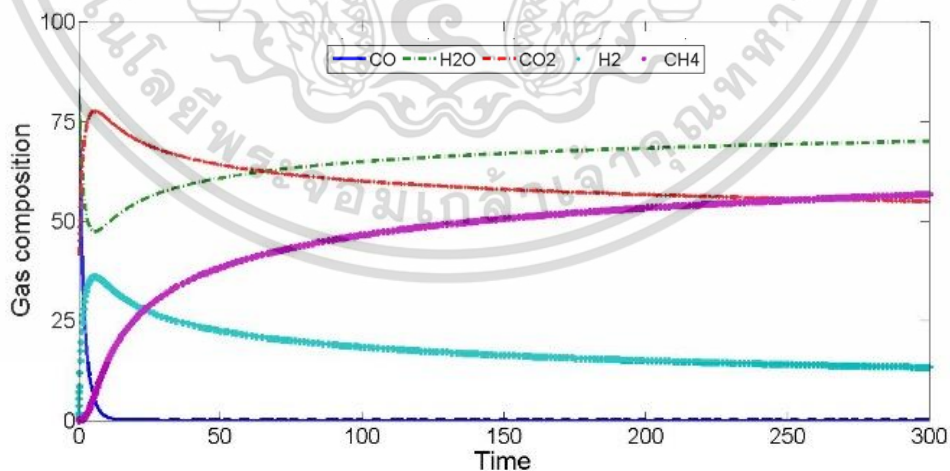


Figure 4.3 Numerical solution of equation 3.3 where  $k_1 = k_2 = 0.75$

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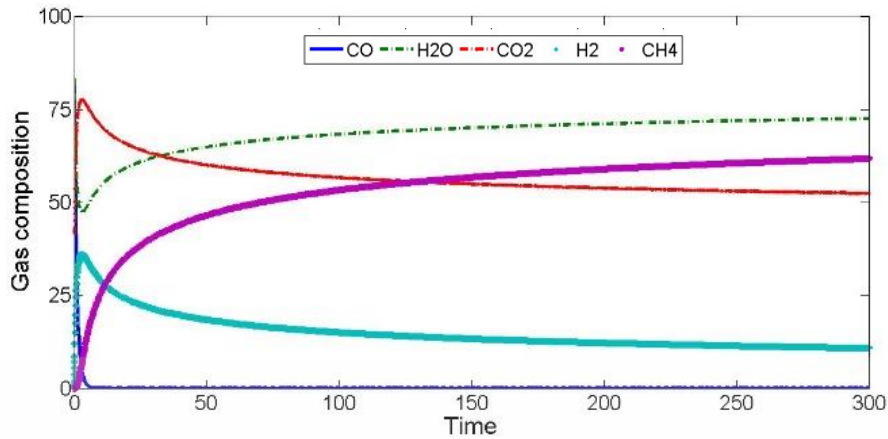


Figure 4.4 Numerical solution of equation 3.3 where  $k_1 = k_2 = 1.5$

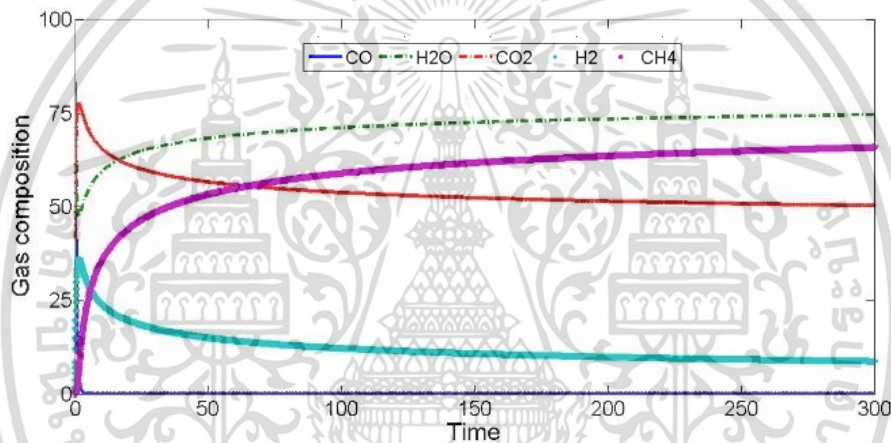


Figure 4.5 Numerical solution of equation 3.3 where  $k_1 = k_2 = 3$

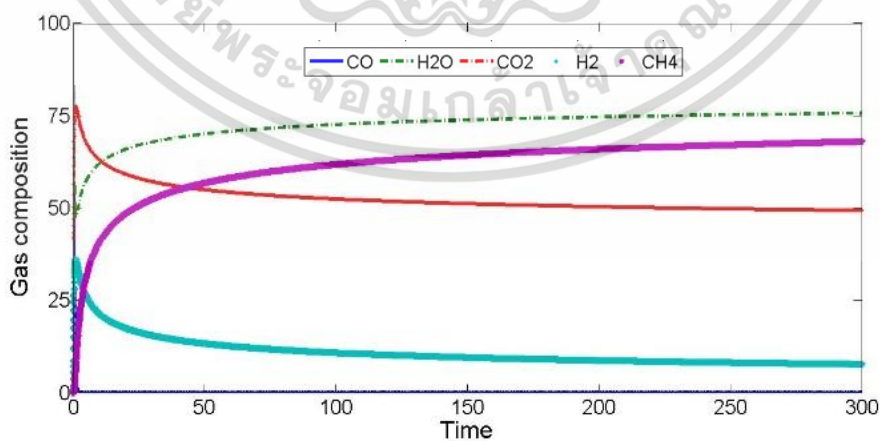


Figure 4.6 Numerical solution of equation 3.3 where  $k_1 = k_2 = 4.5$

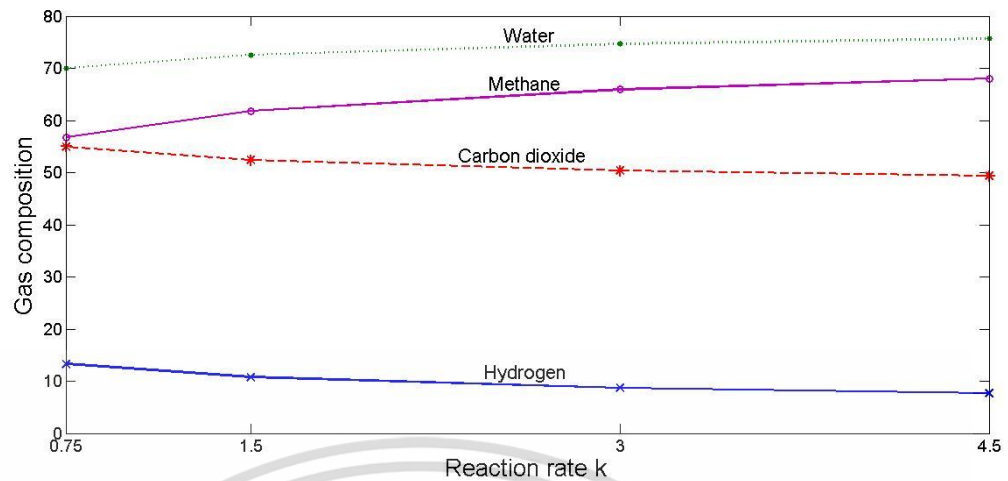
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In Figure 4.3 – 4.6, we consider cases of  $k_1$  and  $k_2$  are equal, 0.75, 1.5, 3.0 and 4.5, respectively. We can conclude that the system will go to phase III and phase IV quickly where the reaction rate increases. The system goes to phase III at the time approximately 6, 3, 2 and 1 for reaction rate  $k_1$  and  $k_2$  are 0.75, 1.50, 3.00, and 4.50, respectively. The numerical results are shown in Table 4.1. Surprisingly, the peak of  $\text{CO}_2$  is 77.65 percentages by volume for all cases. Similarly, an intersection between  $\text{CO}_2$  and  $\text{H}_2\text{O}$  at 62.50 percent and 55.56 percent for  $\text{CO}_2$  and  $\text{CH}_4$ . For a steady time, water is maximum quality (70 – 75 %) for this system. The next sequences are  $\text{CH}_4$ ,  $\text{CO}_2$ , and  $\text{H}_2$  which are 55 – 70, 50 – 55, and 7 – 15 percent by volume. As we can see from the graphs, while  $k_1$  and  $k_2$  are equal and increase, the time duration of phase III is shorter. That is approximately equal to 250, 150, 75 and 50 times for reaction rate 0.25, 1.00 and 1.50 respectively. It is noted that as we can see from Figure 4.6 and Table 4.1, all results reach the fourth phase before time 300. This can be concluded if  $k_1$  and  $k_2$  are equal and small then the system will slowly reach phase IV.

Table 4.1 Values of each result

Value of $k_1$	Value of $k_2$	Peak of $\text{CO}_2$	Crossing of $\text{CO}_2$ and $\text{H}_2\text{O}$	Crossing of $\text{CO}_2$ and $\text{CH}_4$
0.75	0.75	77.65 (time = 5.77)	62.50 (time = 65.31)	55.56 (time = 259.4)
	1.50	75.68 (time = 4.90)	62.45 (time = 35.01)	55.56 (time = 13.13)
	3.00	73.45 (time = 4.08)	62.59 (time = 19.40)	55.56 (time = 68.25)
	4.50	72.07 (time = 3.52)	62.66 (time = 14.27)	55.56 (time = 47.49)
1.50	0.75	79.29 (time = 3.39)	62.47 (time = 63.53)	55.56 (time = 257.40)
	1.50	77.65 (time = 2.89)	62.50 (time = 32.66)	55.56 (time = 129.7)
	3.00	75.68 (time = 2.45)	62.48 (time = 17.50)	55.56 (time = 65.66)
	4.50	74.41 (time = 2.14)	62.44 (time = 12.48)	55.56 (time = 44.98)
3.00	0.75	80.58 (time = 2.20)	62.49 (time = 62.15)	55.56 (time = 256.00)
	1.50	79.29 (time = 1.81)	62.47 (time = 31.77)	55.56 (time = 128.30)
	3.00	77.65 (time = 1.44)	62.50 (time = 16.33)	55.56 (time = 55.56)
	4.50	76.51 (time = 1.38)	62.43 (time = 11.39)	55.56 (time = 43.72)
4.50	0.75	81.19 (time = 1.47)	62.49 (time = 61.71)	55.56 (time = 255.7)
	1.50	80.10 (time = 1.29)	62.51 (time = 31.16)	55.56 (time = 128.2)
	3.00	78.65 (time = 1.05)	62.50 (time = 15.97)	55.56 (time = 64.46)
	4.50	77.65 (time = 0.96)	62.50 (time = 10.83)	55.56 (time = 43.24)

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**Figure 4.7** Relationship between reaction rate  $k$  and gas composition  
where  $k_1 = k_2$  at time = 300

Figure 4.7 describes the relationship between gas composition (water, methane, carbon dioxide, and hydrogen) reaction rate  $k$ . As we can see from the graph, water and methane have direct variation with reaction rate  $k$  while carbon dioxide and hydrogen have inverse variation with reaction rate  $k$ .

We consider the values of  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{H}_2$  at time 300 for reaction rate 0.75, 1.50, 3.00, and 4.50 in Figure 4.6 (see also Table 4.1). Reaction rates are direct variation with water and methane, but it is reverse variation with carbon dioxide and hydrogen. In the equilibrium state, phase IV, this system has the highest concentration of water over 70%. Second is methane between 55 and 70 percent, carbon dioxide is the third sequence about 50 – 55%. Finally, hydrogen has only 5 to 15 percent.

Table 4.1 provides numerical results for  $k_1$  is not equal to  $k_2$  where we consider  $k_1$  and  $k_2$  are 0.75, 1.50, 3.00 and 4.5, respectively. It was found that the maximum value of carbon monoxide is between 70 – 80 percent. They increase as the parameters increase. When we consider the stage where crossing between gasses occur they were found as follows. At the crossing between  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , it appears that the peak values for each case of parameter values are found to be very close (62.5%). Similarly, the crossing values of  $\text{CO}_2$  and  $\text{CH}_4$  are also very close to all cases (55.56%). In addition, the crossing times in both cases are found to be in a similar manner, namely, the larger the parameter values, the shorter the crossing time values.

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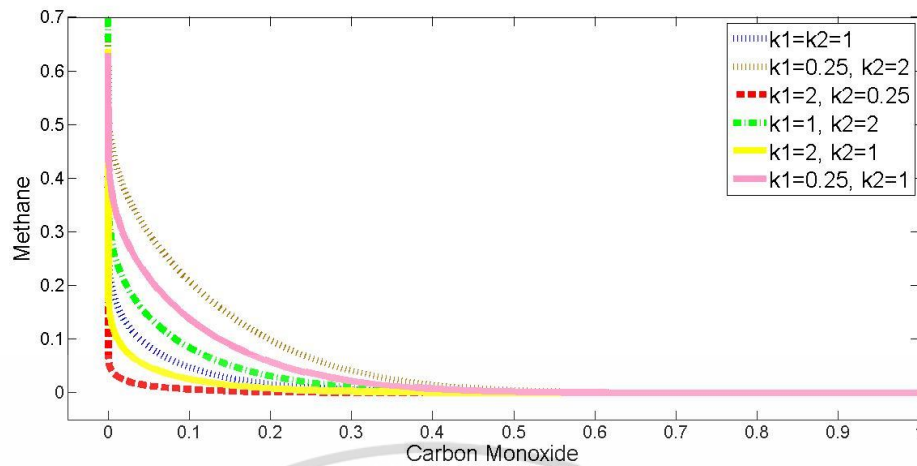


Figure 4.8 Numerical solution of carbon monoxide and methane

Figure 4.8, the relation between carbon dioxide and methane is shown. We consider three cases, namely  $k_1 = k_2 = 1$ ,  $k_1 = 0.25$  and  $k_2 = 2$ ,  $k_1 = 2$  and  $k_2 = 0.25$ . It was found that while carbon monoxide decreases, methane increases which are consistent with equations (7) – (8). Because carbon monoxide is a source for methane production, the increase in methane would occur if carbon monoxide is used and depleted eventually.

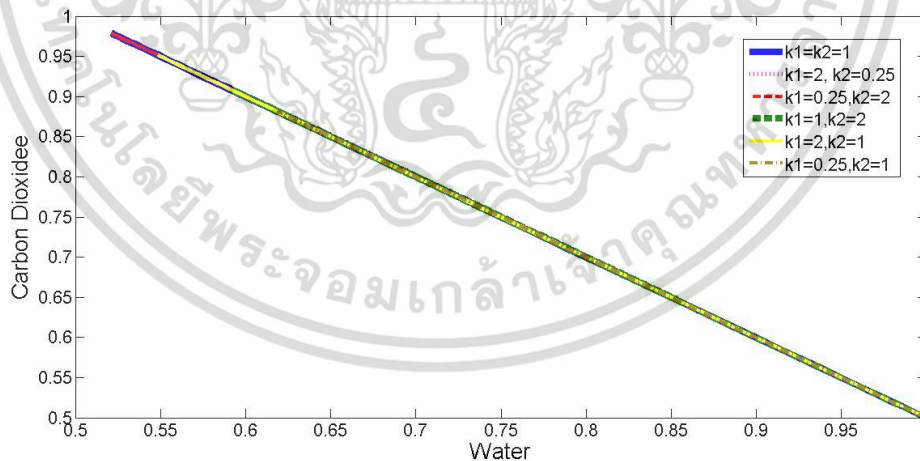


Figure 4.9 Numerical solution of water and carbon dioxide

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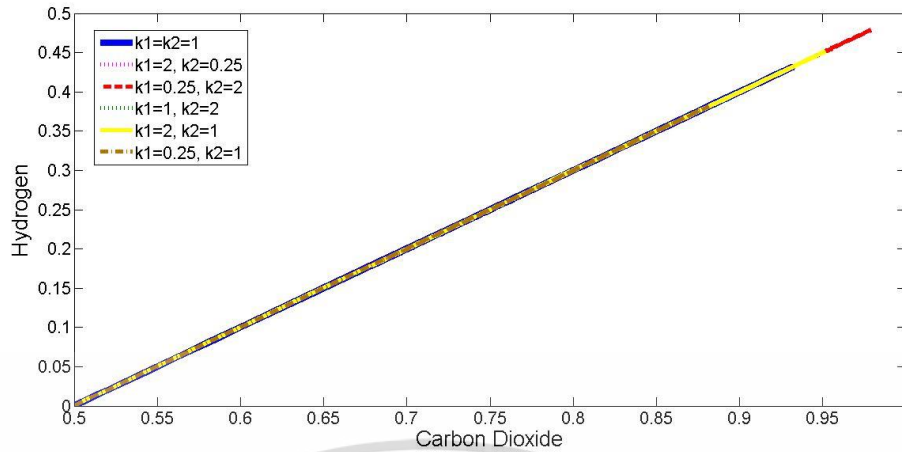


Figure 4.10 Numerical solution of carbon dioxide and hydrogen

Figure 4.9, shows the relation between carbon dioxide and water. As seen from reactions we can see that carbon dioxide is inverse proportional to water. It should be remarked that the rate of change between these two gases does not depend on the parameter values. In Figure 4.10, the relation between carbon dioxide and hydrogen is shown. Similarly to Figure 4.9, the rate of change between these two gases is independent of parameter values.

To sum up, chemical equation (7)–(8) can be described the variation of the anaerobic process of the close landfill by control external factors through the mathematical form of it.

We consider each gas such as CO, CH<sub>4</sub>, CO<sub>2</sub>, H<sub>2</sub>, and H<sub>2</sub>O in case of  $k_1$  equal to  $k_2$  between 0 and 1 as Figure 4.11 – 4.15.

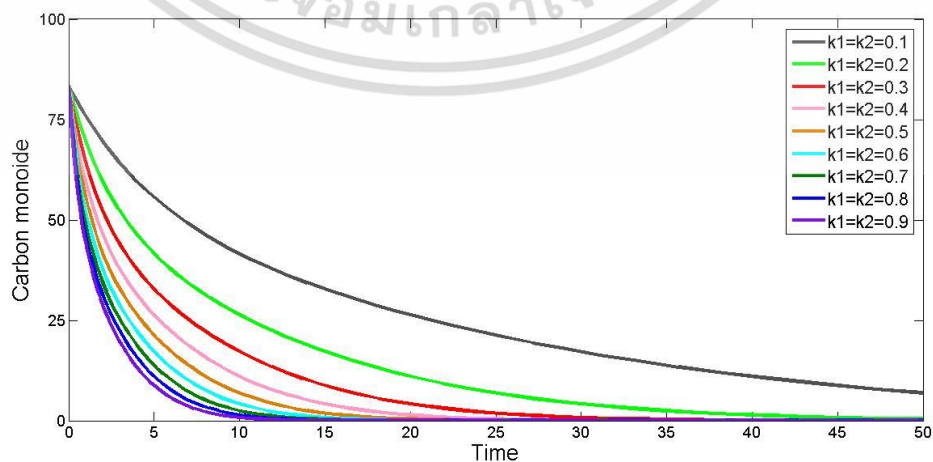


Figure 4.11 Numerical solution of carbon monoxide

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ไม่ว่ากรณีใดๆ ทั้งสิ้น อีกทั้งห้ามมิให้ตัดแปลงเนื้อหา และต้องอ้างอิงถึงเจ้าของเอกสารทุกครั้งที่มีการนำไปใช้

The change of CO likes an exponential curve. It converges to zero with a shorter time where the reaction rate increases as Figure 4.11.

As we can see from Figure 4.12, the graph of CH<sub>4</sub> is logistic growth. The system goes through phase IV quickly where the reaction rate increases.

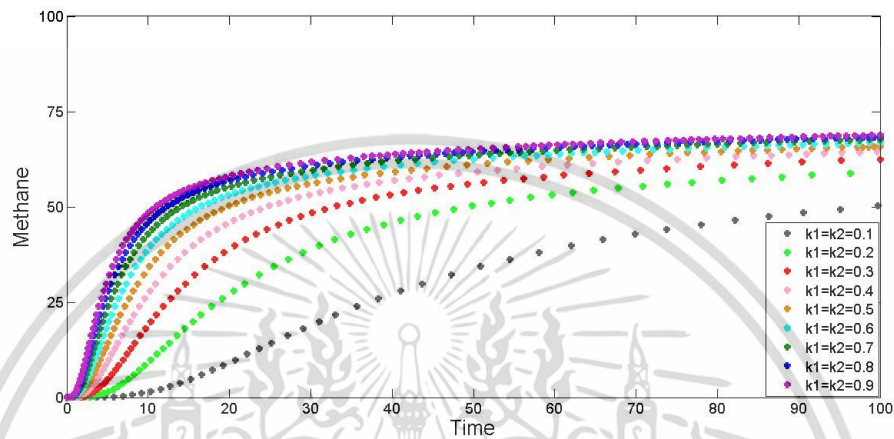


Figure 4.12 Numerical solution of methane

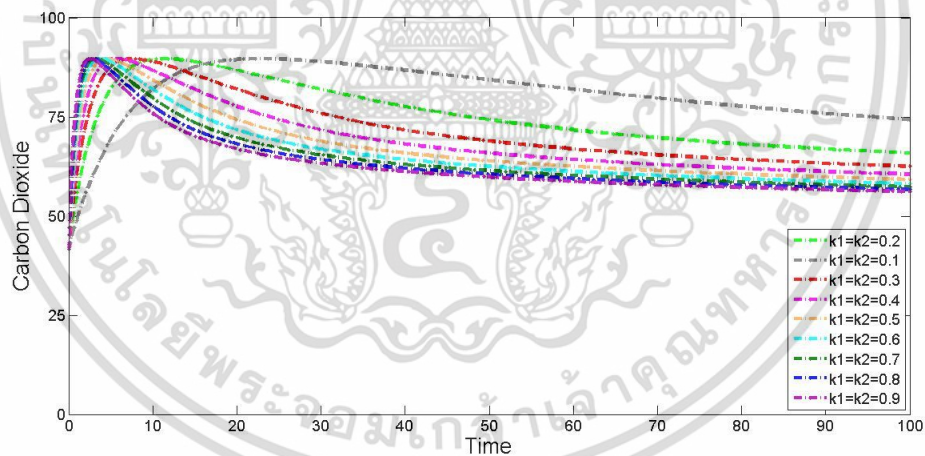


Figure 4.13 Numerical solution of carbon dioxide

The trend of CO<sub>2</sub> (Figure 4.13) is similar to H<sub>2</sub> (Figure 4.14) but the ratio of gas composition is different. This system easily comes to steady-state where the reaction rate increases. The variation of water is a reverse trend where compare with carbon dioxide (Figure 4.15).

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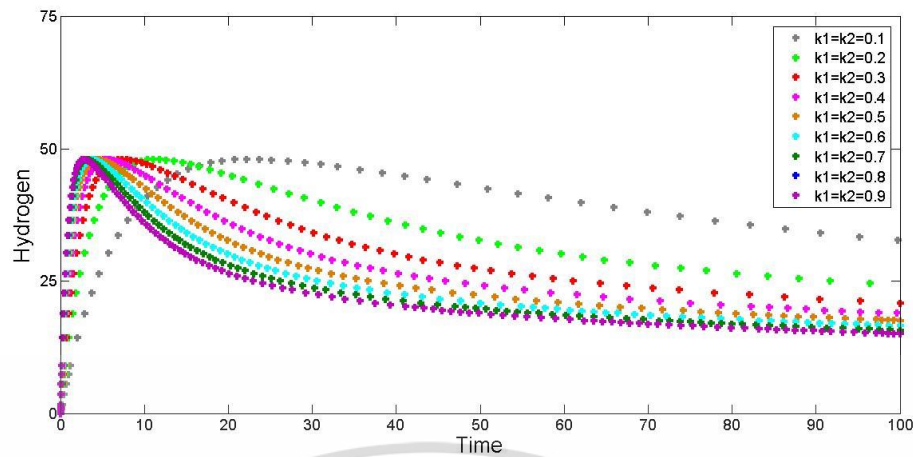


Figure 4.14 Numerical solution of hydrogen

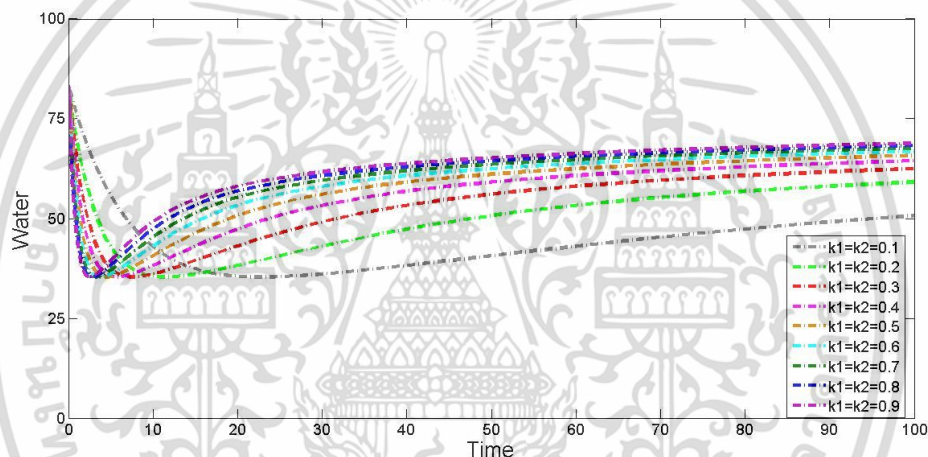


Figure 4.15 Numerical solution of water

## 4.2 Parameter Estimation

$\text{CH}_4$  generation variables such as methane generation rate constant ( $k$ ) and generation potential ( $L_0$ ) are an important factor for several models, Table 4.2 summarizes these parameters and method used to estimation by researches between 2013 and 2017. This table shows the maximum and minimum value of methane generation rate constant and generation potential by different methods such as curve fitting by minimizing the residual sum of squares, curve fitting and linear regression, laboratory experiments, and landfills, minimizing the residual sum of squares, and experimental work

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**Table 4.2** Methane generation rate constant ( $k$ ) and methane generation potential ( $L_0$ )

Authors	Vu et al. (2017)	Fei et al. (2016)	Das et al. (2016)	Wang et al. (2015)	Mou et al. (2015)	Amini et al. (2013)
$k$ min	0.010	0.180	0.030	0.090	0.013	0.040
$k$ max	0.048	5.66	0.080	0.120	0.190	0.090
$L_0$ min	44	88	34	55	8	93
$L_0$ max	100	98	48	100	107	144
Method	Curve fitting by minimizing residual sum of squares	Laboratory experiments and landfills	Undefined	Minimizing residual sum of squares	Experimental work	Curve fitting and linear regression

### 4.3 Discussion

Values of reaction rate  $k_1$  and  $k_2$  affect to steady-state and variation of gases in a closed landfill system. As equation (2.10),  $k_1$  affects the increase of carbon dioxide and hydrogen which depend on carbon monoxide and water. Another one, equation (2.11), the products of equation (2.10) affect the increase of methane and water. These two equations can describe the variation of methane and carbon dioxide agree with the physical phenomenon (Figure 2.1). Since this model is not considered measured data from landfill sites, precisely the time of the model cannot be indicated. It leads to we can indicate the specific value of reaction rate  $k_1$  and  $k_2$  but we can classify it into three cases:

If  $k_1$  equals to  $k_2$  and values of it are huge, the system will go to steady-state quickly. Time to steady-state is a direct variation to the value of reaction rates.

If  $k_1$  is more than  $k_2$  and huge difference, the system will go to steady-state quickly. Time to steady-state is a direct variation to the difference in reaction rates.

If  $k_1$  is less than  $k_2$  and huge difference, the system will go to steady-state quickly where compare with the case of  $k_1$  is more than  $k_2$ . But if  $k_1$  is less than  $k_2$  and tiny difference, the system will go to steady state slowly. Time to steady-state is a direct variation to the difference in reaction rates.



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## Chapter 5

# Conclusions and Suggestions

### 5.1 Conclusions

This paper presents a comprehensive review of different models for landfill gas emission, especially models of methane emission. The most popular models (TNO, Afvalzorg, EPER Germany, LandGEM, and IPCC models) were summarized to describe the advantages, disadvantages, and parameters of each. It also discussed computer simulation models which formed six parts of research in the series “Computer simulation of gas generation, and transport in landfills” using a three dimensional model with complex techniques, such as artificial neural network and genetic algorithm. Other models were also supported for computer simulation models with different techniques. Besides, the application section recommended how to find optimal parameters and methods for a landfill.

Moreover, the dynamic characteristics of greenhouse gases generated from the closed landfill system were studied. The involved chemical reaction processes are considered and the mathematical model was formulated and analyzed. The behaviors of the key greenhouse gasses namely carbon dioxide and methane are carefully studied. It was found that our proposed model is qualitatively in good agreement with the real-world phenomena. The characteristics of greenhouse gasses of interest namely carbon dioxide and methane were found to depend on the reaction rate in complex manners. Since the system is closed each gas species becomes a constraint to one another. We can utilize these findings to control the landfill system and to take benefit from the useful products. For example, it is better for the situation of  $k_1$  less than  $k_2$  leading the system to quickly reaching phase four. As a result, methane would be abundance where  $k_2$  is large. Hence if we can control these reactants, we can take advantage of the landfill greatly. Moreover, it suggests that methane and carbon dioxide could be used for electricity generation which helps reduce greenhouse gas in the atmosphere.

## 5.2 Suggestions

The mathematical model of these studies can support chemical phenomena of the landfill process which time of each process depend on location, size, and materials used to construction.



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## Modelling Greenhouse Gas Generation for Landfill

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**Abstract** - Landfill has been widely used in many countries for the final disposal of solid waste material due to its economic advantages. Landfills emit mostly methane and carbon dioxide. In this work, the dynamic characteristics of greenhouse gases generated from the closed landfill system were studied. The chemical reaction processes involved are considered and a mathematical model is formulated and analyzed. The behaviors of the key greenhouse gases, namely, carbon dioxide and methane, are carefully studied. It was found that our proposed model is qualitatively in good agreement with the real world phenomena. The characteristics of greenhouse gases of interest namely carbon dioxide and methane were found to depend on the reaction rate in a complex manner. Since the system is closed, each gas species becomes a constraint to one another. We can utilize these findings to control the landfill system and to take benefit from the useful products. Moreover, it suggests that methane and carbon dioxide could be used for electricity generation which helps reduce greenhouse gases in atmosphere.

**Keywords** - Landfill; Waste; Greenhouse gas; Mathematical model; ODE

### I. INTRODUCTION

Landfilling is one of the most commonly adopted technologies for refuse disposal [1]. Landfill methods continue to be widely used in different countries for the final disposal of solid waste material due to its economic advantages [2]. However, a lot of greenhouse gas, especially CO<sub>2</sub> and CH<sub>4</sub>, is produced in the landfill waste management process. Therefore, to reduce greenhouse gases, governments around the world are encouraging projects that turn landfill gas into electricity. Landfill methane has the potential to produce 2,700 MW of electric generating capacity in the United States alone and 9,000 MW worldwide.

Landfill gases are mixtures of several gases with its main constituents being methane 50 – 55% and carbon dioxide 45 – 55% [3]. It is aerobic and anaerobic decomposition which mainly generates methane and carbon dioxide, respectively. Methane is regarded as one of the most important greenhouse gases because its global warming potential over decades is 28 times higher than carbon dioxide [1,4-7]. Hence, studying generation of

methane and carbon dioxide is one of the interesting research areas especially from the greenhouse gases view point [2,8]. Global warming is one of a number of environmental impacts that derived from solid waste management options. Several research works focused on the landfill system and related gases in connection with the environmental problem [9].

Besides the experimental and empirical research approach to study the landfill system, mathematical modeling is one of the alternative tools to uncover this complex system problem [10,11]. The mathematical model is a representation in mathematical terms of the behavior of real world systems or objects. Mathematical models are quick and easy to produce; they can simplify a more complex situation which can help us improve our understanding of the real world as certain variables. Moreover, it enables predictions to be made or can help provide control [10,11,12]. It can take many forms, such as dynamical systems, statistical models, or differential equations [13]. And using the systems of ODE is one of very well-known method [14]. In the system of differential equations model, the most important consideration is equilibrium or steady state. In addition,

the analysis of the system parameters influencing the system dynamics or behavior is also a common consideration.

In this work, we focus on the behavior of greenhouse gases generated from the closed landfill system. The involved chemical reaction processes are considered and a mathematical model is formulated and analyzed. The behaviors of carbon dioxide and methane are carefully studied. We will present numerical data and discussion to provide the new findings.

## II. LITERATURE REVIEW AND LIMITATIONS OF CURRENT MODELS.

Mathematical modelling on the landfill system is one of great interest research problems [20-23]. Omar and Rohani solved the model equations using the finite element method with the commercially available software COMSOL Multiphysics® [24]. Cuartas et al proposed the new method for the analysis and optimization of design variables in waste landfills [25]. Kormi et al presented a cost-effective method to estimate methane emissions using ambient air methane measurements taken within a landfill. They applied stochastic search techniques combined with the standard Gaussian dispersion model to identify locations and emission rates of potential emission sources [26]. Bian et al investigated a model that combines the multicomponent diffusive equation and Darcy's law, coupled with the dual Monod kinetic equation, to simulate CH<sub>4</sub> transport, oxidation and emission in landfill cover soils [27]. Still to the best of our knowledge, there is no first step model focusing on the system of greenhouse gases, namely methane and carbon dioxide. Here we propose the new model that even it is simple but can demonstrate how system dynamic of landfill gas generation work. Moreover, changes in typical landfill gas composition over time or phase is revealed considerably.

The limitations of the current models are as follow. Firstly, here we consider the closed system which in the real world system is quite complicated to control. It is usually the case where there some more or less gas molecules going into or out from the system. For the closed system, it is the constraint that the gasses of interest will reach equilibrium. This is according to the limitation of the gas number. Secondly, in our system we use the condition where the phase I is barely not observation due to its small time scale. Therefore, this model would be well applied for the consideration from the phase II. Still we believe that it would not affect the quality of the model as far as methane and carbon dioxide are the main focus. Thirdly, the reaction rates being used here are all constant. In the real situations, they generally depend on temperature, material concentrations, and space-time.

## III. MODEL FORMULATION

In this section, the chemical reactions of greenhouse gas in a closed system are presented and a ODEs system model is formulated. To clearly understand our system model and results, we briefly review the relevant compositions and changes in the landfill system as follows.

### A. Real World System Background

Typically, the decomposition of refuse to methane in landfills is a microbial mediated process which requires the coordinated activity of several trophic groups of bacteria [15]. The composition of the gas produced changes with each of the four phases of decomposition.

*A1. Phase I – Aerobic Phase (Hydrolysis):* During the first phase of decomposition, aerobic bacteria can survive and grow in an oxygenated environment. They consume oxygen while breaking down the long molecular chains of complex carbohydrates, proteins, and lipids that comprise organic waste. As you can see from Fig.1 [3], there is 80% N<sub>2</sub> and 20% O<sub>2</sub> at the beginning. Both of oxygen and nitrate are consumed. The primary by product of this process is carbon dioxide and hydrogen. Phase I continues until the available oxygen is depleted. The gas composition will be around 25% CO<sub>2</sub> and 10% H<sub>2</sub>.

*A2. Phase II – Anaerobic Phase (Acidification):* Phase II decomposition starts after the oxygen in the landfill has been used up. Bacteria convert compounds created by anaerobic bacteria (a process without an oxygen requirement) into acetic, lactic, and formic acids and alcohols such as methanol and ethanol. The landfill becomes highly acidic. The gaseous by products of this process are CO<sub>2</sub> and H<sub>2</sub>; the N<sub>2</sub> content of the gas decreases during this phase and is nearly completely displaced at the end of the phase; the pH decreases. As you can see from Fig. 1 carbon dioxide increases from 25% to 65% by the end of phase II. Hydrogen increases slowly from 10% to 20% [16].

*A3. Phase III – Initial Methanogenic Phase (Acetogenesis):* The landfill becomes a more neutral environment when methane producing bacteria began to establish themselves. Acid - producing bacteria create compounds for the methanogenic bacteria to consume. Methanogenic bacteria consume the carbon dioxide and acetate. In this phase, there is a rapid increase in rate of methane production to about 50% of gas composition. The increase of CH<sub>4</sub> production is associated with a decrease of CO<sub>2</sub> (from 65% to nearly 50%) and H<sub>2</sub>; pH slowly increases.



$$\begin{aligned}
 \frac{d[CO_2]}{dt} &= -k_2[CO_2][H_2]^4 \\
 \frac{d[H_2]}{dt} &= -k_2[CO_2][H_2]^4 \\
 \frac{d[CH_4]}{dt} &= k_2[CO_2][H_2]^4 \\
 \frac{d[H_2O]}{dt} &= k_2[CO_2][H_2]^4
 \end{aligned}
 \tag{10}$$

For the chemical reaction (8), the change of each gas depends on CO<sub>2</sub> and H<sub>2</sub> and decreases with rate k<sub>2</sub> while CH<sub>4</sub> and H<sub>2</sub>O increase with rate k<sub>2</sub>. From (9) and (10), each gas has two differential equations to explain its variation. Therefore, we can conclude that:

$$\begin{aligned}
 \frac{d[CO]}{dt} &= -k_1[CO][H_2O] \\
 \frac{d[H_2O]}{dt} &= -k_1[CO][H_2O] + k_2[CO_2][H_2]^4 \\
 \frac{d[CO_2]}{dt} &= k_1[CO][H_2O] - k_2[CO_2][H_2]^4 \\
 \frac{d[H_2]}{dt} &= k_1[CO][H_2O] - k_2[CO_2][H_2]^4 \\
 \frac{d[CH_4]}{dt} &= k_2[CO_2][H_2]^4
 \end{aligned}
 \tag{11}$$

It is seen that equation (11) is a set of nonlinear first order ODEs. To understand the system dynamics, we apply numerical methods to solve it. It should be remarked that for the sake of simplicity we redefine reaction rates k<sub>1</sub>, k<sub>2</sub>, k<sub>1</sub>' = 0.5k<sub>1</sub> and k<sub>2</sub>' = 0.5k<sub>2</sub> for the numerical analysis.

#### IV. RESULTS AND DISCUSSION

We applied the Runge – Kutta method via MATLAB R2013a ode45 to solve the system. Each result takes a few minutes to get the data from time 0 up to time 300.

Since it is very important to validate our model, we generate the data to see if our numerical data are consistent with those data given in Fig. 1. From Fig.1, as mentioned previously, there are four phases in the reaction landfill system. Phase I features the increase in CO<sub>2</sub> from almost null. This phase is aerobic phase by nature and not included in our model study, meaning we consider the system dynamics from the anaerobic phase (phase II) to Phase IV.

Fig. 2 shows typical solution curves for the case of k<sub>1</sub> = k<sub>2</sub> = 4, where we take initial values for CO, H<sub>2</sub>O, CO<sub>2</sub>, H<sub>2</sub> and CH<sub>4</sub> as 1, 1, 0.5, 0, and 0 respectively.

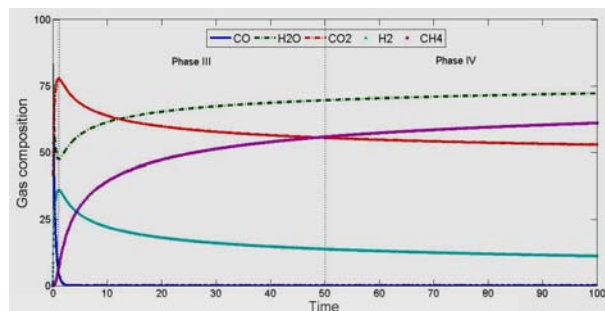


Figure 2. Numerical solution of (11) with k<sub>1</sub> = k<sub>2</sub> = 4.

The results are at least qualitatively consistent with those shown in Fig.1. Here our solutions include water and carbon monoxide for the sake of understanding. The data of CO<sub>2</sub> and H<sub>2</sub> has the same trend. Apparently, H<sub>2</sub> in this system slowly decreases. Since the data in Fig. 2 does not clearly show what changes in the second phase, we magnify the results between time 0 and 5: Fig. 3 clearly shows the second and third phase which is divided by the peak of carbon dioxide as mentioned before.

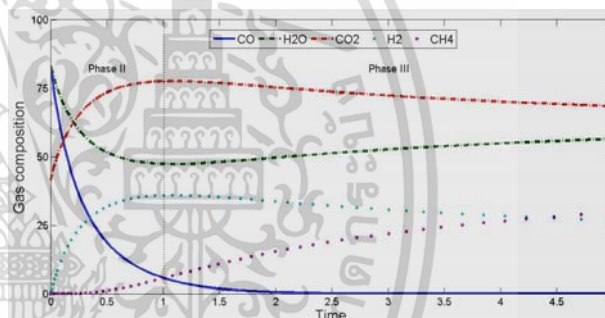


Figure 3. Numerical solution of (11) with k<sub>1</sub> = k<sub>2</sub> = 4

In Fig. 4, we consider four cases when k<sub>1</sub>=k<sub>2</sub>. The numerical results are shown in Fig. 4a – d and Table 1.

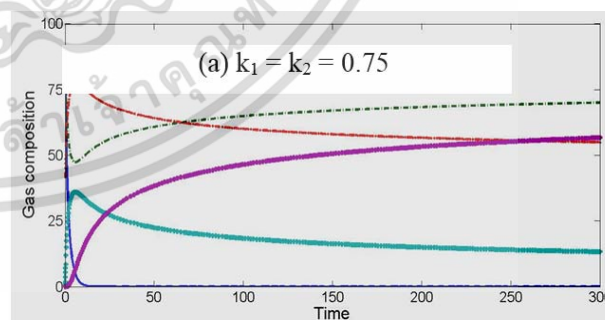


Figure 4. Results of (11) with k<sub>1</sub> = k<sub>2</sub> = 0.75. More results on next page.

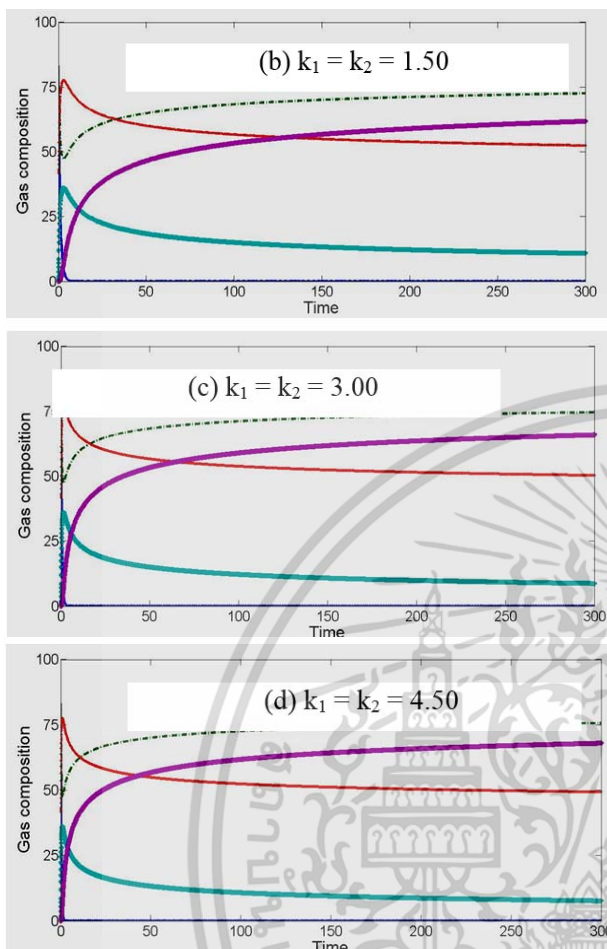


Figure 4. Results of (11) with  $k_1 = k_2$ .

Surprisingly, the peak of CO<sub>2</sub> is 78% by volume for all cases. Similarly, the intersection between CO<sub>2</sub> and H<sub>2</sub>O graph is at 62.5% and 55.6% for CO<sub>2</sub> and CH<sub>4</sub>, respectively. At steady state time, water is at maximum quality (70 – 75 %) for this system. The next sequences are CH<sub>4</sub>, CO<sub>2</sub> and H<sub>2</sub> which are 55 – 70, 50 – 55, and 7 – 15 percent by volume. As we can see from the graphs, while  $k_1$  and  $k_2$  are equal and increase, the length of phase III gets shorter. The lengths are approximately equal to 250, 150, 75 and 50 units for reaction rates 0.25, 1.00 and 1.50 respectively.

It is noted that, as we can see from Fig. 4 and Table I, all results reach the fourth phase time before time=300. It can be concluded that if  $k_1$  and  $k_2$  are equal and small then the system will slowly reach phase IV.

We consider values of H<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub> and H<sub>2</sub> at time=300 for reaction rates 0.75, 1.50, 3.00, and 4.50 in Fig. 5 (see also Table I).

Water and methane increase with increasing reaction rate, but carbon dioxide and hydrogen decrease. In equilibrium state, phase IV, this system has the highest concentration of water (over 70%). Second is methane

between 55 and 70 percent, carbon dioxide is third sequence (about 50 – 55%). Finally, hydrogen is only 5 to 15 percent.

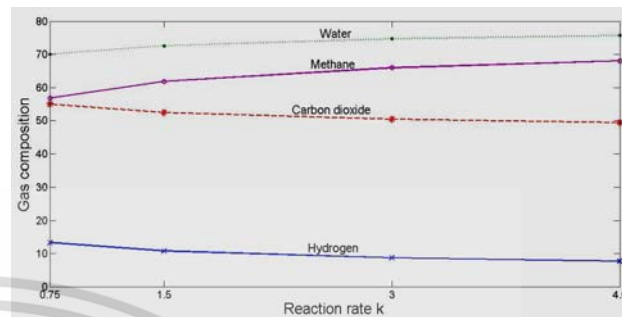


Figure 5. Relationship between reaction rate  $k$  and gas composition where  $k_1 = k_2$  at time = 300

Table I provides numerical results for  $k_1$  not equal to  $k_2$ . It was found that the maximum value of carbon monoxide is in between 70 – 80 percent.

TABLE I. VALUES OF EACH RESULT

$k_1$	$k_2$	Peak of CO <sub>2</sub>	Crossing of CO <sub>2</sub> and H <sub>2</sub> O	Crossing of CO <sub>2</sub> and CH <sub>4</sub>
0.75	0.75	77.65 (time=5.77)	62.50 (time=65.31)	55.56 (time=259.4)
	1.50	75.68 (time=4.90)	62.45 (time=35.01)	55.56 (time=13.13)
	3.00	73.45 (time=4.08)	62.59 (time=19.40)	55.56 (time=68.25)
	4.50	72.07 (time=3.52)	62.66 (time=14.27)	55.56 (time=47.49)
1.50	0.75	79.29 (time=3.39)	62.47 (time=63.53)	55.56 (time=257.40)
	1.50	77.65 (time=2.89)	62.50 (time=32.66)	55.56 (time=129.7)
	3.00	75.68 (time=2.45)	62.48 (time=17.50)	55.56 (time=65.66)
	4.50	74.41 (time=2.14)	62.44 (time=12.48)	55.56 (time=44.98)
3.00	0.75	80.58 (time=2.20)	62.49 (time=62.15)	55.56 (time=256.00)
	1.50	79.29 (time=1.81)	62.47 (time=31.77)	55.56 (time=128.30)
	3.00	77.65 (time=1.44)	62.50 (time=16.33)	55.56 (time=55.56)
	4.50	76.51 (time=1.38)	62.43 (time=11.39)	55.56 (time=43.72)
4.50	0.75	81.19 (time=1.47)	62.49 (time=61.71)	55.56 (time=255.7)
	1.50	80.10 (time=1.29)	62.51 (time=31.16)	55.56 (time=128.2)
	3.00	78.65 (time=1.05)	62.50 (time=15.97)	55.56 (time=64.46)
	4.50	77.65 (time=0.96)	62.50 (time=10.83)	55.56 (time=43.24)

This increases as the parameters increase. When we consider the stage where crossing between gases occurs they were found as follows. At the crossing between CO<sub>2</sub> and H<sub>2</sub>O, it appears that the peak values for each case of

the parameter values are found to be very close (62.5%). Similarly, the crossing values of CO<sub>2</sub> and CH<sub>4</sub> are also very close in all cases (55.56%). In addition, the crossing times in both cases are found to be in a similar manner, namely, the larger the parameter values, the shorter the crossing time values.

In Fig. 6, the relation between carbon dioxide and methane is shown. We consider three cases, namely,  $k_1 = k_2 = 1$ ,  $k_1 = 0.25$  and  $k_2 = 2$ ,  $k_1 = 2$  and  $k_2 = 0.25$ .

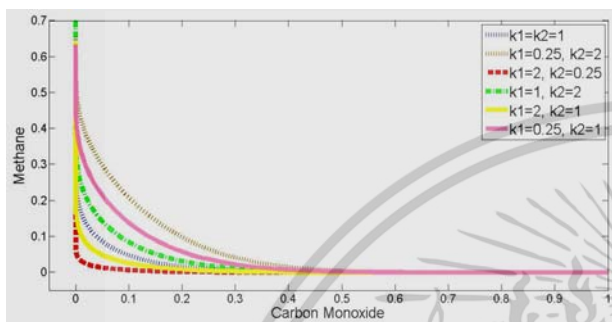


Figure 6. Numerical solution of carbon monoxide and methane

It was found that while carbon monoxide decreases, methane increases which is consistent with eq. (7) – (8). Because carbon monoxide is a source for methane production, the increase in methane would occur if carbon monoxide is used and depleted eventually.

Fig. 7 shows the relation between carbon dioxide and water.

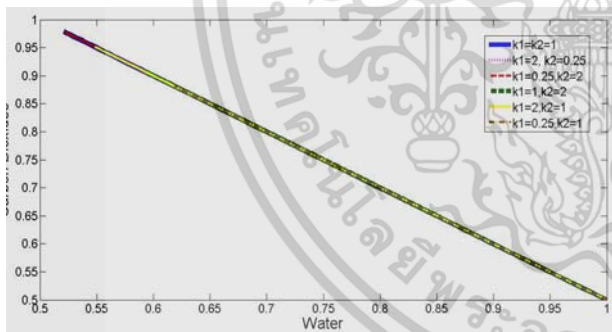


Figure 7. Numerical solution of water and carbon dioxide

As seen from reactions it is clear that carbon dioxide concentration is inversely proportional to water. It should be remarked that the rate of change between these two gases does not depend on the parameter values.

In Fig. 8, the relation between carbon dioxide and hydrogen is shown. In similar manner to Fig. 7, the rate of change between these two gases is independent of the parameter values.

To sum up, (7) and (8) describe the variation of anaerobic processes of closed landfill by control of external factors through a mathematical model.

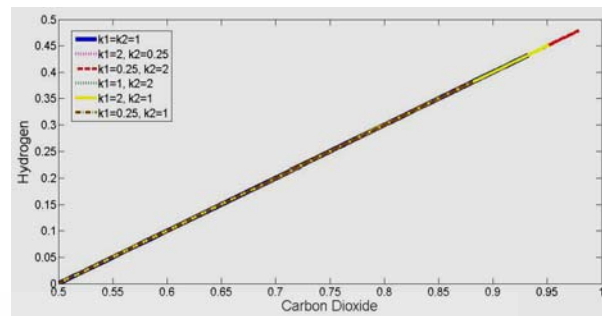


Figure 8. Numerical solution of carbon dioxide and hydrogen.

## V. CONCLUSION

In this work, the dynamical characteristics of greenhouse gases generated from a closed landfill system were studied. The chemical reaction involved are considered and a mathematical model was formulated and analyzed. The behaviors of the key greenhouse gases, namely, carbon dioxide and methane, are carefully studied. It was found that our proposed model is qualitatively in good agreement with the real world phenomena. The characteristics of carbon dioxide and methane were found to depend on the reaction rate in a complex manner. Since the system is closed, each gas species becomes a constraint on one another. We can utilize these findings to control the landfill system and to take benefit from the useful products. For example it is better to make  $k_1$  less than  $k_2$  as this leads to the system to quickly reach phase four. As a result, there would be abundance of methane when  $k_2$  is large. Hence if we can control these reactants, we can take advantage of the landfill greatly.

## ACKNOWLEDGMENT

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The seal of the National Library of Thailand is a circular emblem. It features a central sunburst with rays emanating from a central point. Below the sunburst are three tiered stupas or pagodas, each supported by a decorative base. The entire emblem is surrounded by a circular border containing Thai text. The text at the top reads "กรมหอสมุดแห่งชาติ" (National Library of Thailand) and the text at the bottom reads "พระจอมเกล้าเจ้าคุณทหารลาดกระบัง" (King Chulalongkornrajavidyalaya University, Ladkrabang).

Appendix B  
Academic Publication II

เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้งานเพื่อการศึกษาเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า  
ไม่ว่ากรณีใดๆ ทั้งสิ้น อีกทั้งห้ามมิให้ดัดแปลงเนื้อหา และต้องอ้างอิงถึงเจ้าของเอกสารทุกครั้งที่มีการนำไปใช้

# A Review of Modeling and Computer Simulation of Landfill Gas

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**Abstract**—A landfill is one of the most popular forms of waste management around the world. Most research has focused on leachate, or gas, in a landfill system, which needs to be tightly controlled to ensure that no explosions occur, among other concerns. Landfill gas can be used for electricity generation and, when properly managed, can reduce air and waste pollution. This work reviews articles related to the following: (i) estimation models for methane generation in the landfill, (ii) various computer simulation techniques and their assumptions, and (iii) application of those models and techniques. This paper also describes and compares the advantages and disadvantages of recent methane emission models and computer simulation techniques, as well as their real-world applications.)

**Keywords**—Waste Management; Landfill; Greenhouse gas; Modeling; Computer Simulation

## I. INTRODUCTION

Following the rapid increase in world population and unprecedented urbanization, waste is generated in larger and larger amounts, particularly in cities, and especially in developing countries (Yang et al., 2018). One million metric tons of waste is generated daily around the world. Its mismanagement directly affects human health because of its harmful contaminants and gases emitted into the environment. Moreover, mismanagement of germ-containing waste can lead to widespread contagious disease carried by insects. In addition, waste has been reported to cause cancer in the populations living near landfill sites (Giusti et al., 2009). Proper waste management eliminates

adverse impacts on the environment and human health (Dawane et al., 2015).

### A. Waste management

Effective waste management, especially of toxic materials, is a major challenge for global sustainable development. A range of methods is available for the disposal or treatment of waste, including incineration, composting, recycling, and landfill. Incineration is one of the most popular treatment techniques in many areas, because of its ability to reduce waste mass by 70%, and volume by up to 90%. This method is an electricity generation process, consisting of three steps, namely, incineration, energy recovery, and air pollution control, which concerns air pollutants such as  $\text{SO}_x$ ,  $\text{CO}_x$ , and  $\text{NO}_x$ . There are many advantages to this technique, such

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ไม่ว่ากรณีใดๆ ทั้งสิ้น อีกทั้งห้ามมิให้ตัดแปลงเนื้อหา และต้องอ้างอิงถึงเจ้าของเอกสารทุกครั้งที่มีการนำไปใช้

as it is the most suitable for high calorific value waste; units with high throughput and continuous feed can be set up; thermal energy can be harnessed for power generation or direct heating; it being relatively noiseless and odorless; low land space is required; it can reduce transportation costs, and it is hygienic. In contrast, the disadvantages include it being the least suited for aqueous, high moisture content, low calorific value, and chlorinated waste; toxic particulate emissions; the high cost, and the overall efficiency of small power stations being low. Recycling means the process of converting waste materials into new materials. This technique is an alternative to conventional waste disposal, can save materials, and help lower greenhouse gas emissions. Glass, paper, plastic, and metals, such as aluminum and steel, are all commonly recycled.

Composting is the biological process of breaking up organic waste, especially found in organic farming, into extremely useful humus by various micro-organisms, including bacteria and fungi. Composting is often described as nature's way of recycling and is a key ingredient in organic farming. Landfill gas recovery is the least costly option in which gas produced can be utilized for power generation or direct thermal application. However, surface runoff during rainfall can cause pollution, especially where soil and groundwater may be polluted by leachate. Moreover, this way has significant transportation costs (Daniel et al., 2018; Khanjan et al., 2014). Landfill remains the most widely used approach in the developing world due to its low cost. However, improper management can result in major health and environmental problems (Marion et al., 2008).

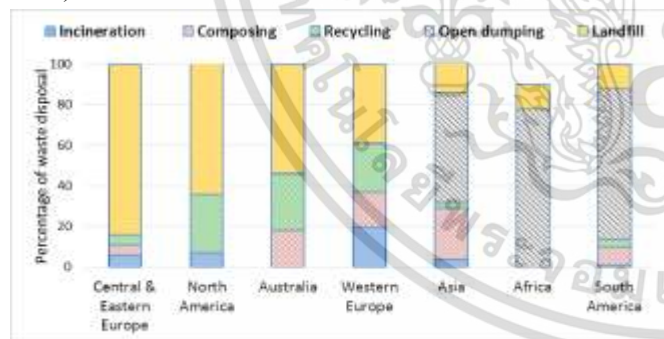


Figure 1. Waste disposal worldwide by region (modified from Khanjan et al., 2014)

Waste treatments worldwide, in Figure 1, are divided into six different regions (Central and Eastern Europe, Western Europe, North America, South America, Africa, Australia, and Asia). Open dumping is defined as land disposal where the waste is disposed of without proper control and without environmental protection. This way is inexpensive, but harms human health, and can lead to air and water pollution. As we can see from the graph, the most commonly accepted methods of waste disposal are open

dumping and landfill in several areas around the world. Asia, Africa, and South America prefer open dumping, while landfill is the most popular technique for the other areas (Khanjan et al., 2014; The Statistics Portal, 2018). Moreover, a major part of this waste is treated by landfill, which has its own influence over the land and environment (Dawane et al., 2015).

### B. Landfill

Landfilling is one of the most commonly adopted technologies for refuse disposal. Landfill methods continue to be widely used in different countries for the final disposal of solid waste material due to their economic advantages. There are two majors to consider in landfill: leachate and landfill gas. Leachate is a release from sanitary landfill, consisting mainly of leachate, which has become the subject of recent interest in strongly polluted wastewater and biogas, which is a resource which can be utilized for energy production (Renou et al., 2008; Tchobanoglous et al., 1994). However, a lot of greenhouse gases, especially CO<sub>2</sub> and CH<sub>4</sub>, are products in landfill waste management processes. Therefore, to reduce greenhouse gases, governments around the world are encouraging projects that turn landfill gas to electricity. The collection and utilization of this valuable renewable energy source for power generation are seen worldwide. Landfill methane is abundant and readily sourced. There is the potential to produce 2,700 MW of electricity generating capacity in the United States alone, and 9,000 MW worldwide (Uising et al., 2017).

Landfill gases are mixtures of several gases, with its main constituents being methane and carbon dioxide, being the main gases produced by the landfill process (Landfill Methane Outreach Program, 2018). This is an alternative method of methane and carbon dioxide emission control, which can be created by the reaction of certain chemicals presented in waste. This process can be divided into two main parts, aerobic and anaerobic decomposition, which mainly generate methane and carbon dioxide. Methane is regarded as one of the most important greenhouse gases because its global warming potential is 28 times higher than carbon dioxide (Landfill Methane Outreach Program, 2018; Johari et al., 2012; Jha et al., 2008; Chen et al., 2008; Pachauri et al., 2014). Hence, studying the generation of methane and carbon dioxide is one of the most interesting research areas, especially from the greenhouse gas viewpoint (Tchobanoglous et al., 1994; Themelis et al., 2007). The occurrence of carbon monoxide (CO) and its reaction can eventually perform chemical reactions with other gases such as CO<sub>2</sub>, CH<sub>4</sub>, and O<sub>3</sub>, thereby generating greenhouse gases and causing global warming (Seinfeld et al., 1998; Letcher et al., 2011; Raub et al., 2000). Global warming is one of a number of environmental impacts derived from solid waste management options. Several research works have focused on landfill system-related

gases in connection with environmental problems (Lisk, 1991).

Anaerobic digestion is a process of microbial degradation of several trophic groups of bacteria. The quality of the generated biogas depends on the process parameters and substrate composition; the biogas is typically composed of 50 – 75 % CH<sub>4</sub>, 25 – 50 % CO<sub>2</sub>, and 1 – 15 % of other gases (Marion et al., 2008; Daniel et al., 1993; Noor et al., 2013). The composition of the gas produced changes with each of the four phases of decomposition.

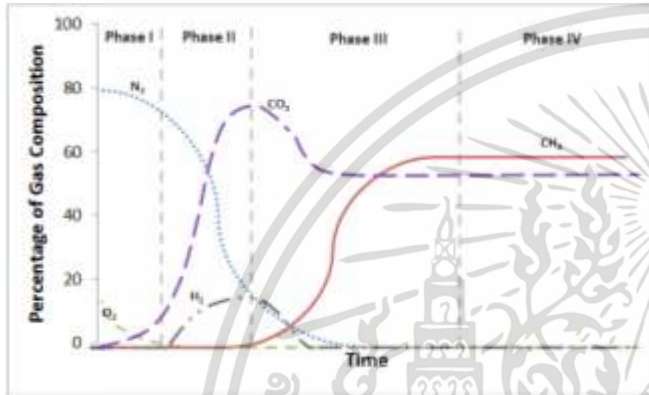


Figure 2. Changes in typical landfill gas composition after waste placement (adapted from Tchobanoglous et al., 1994)

The first phase is hydrolysis, or aerobic degradation, in which the aerobic bacteria digest complex organic matter into CO<sub>2</sub> and H<sub>2</sub>O. The second phase is acidification, or the anaerobic phase, in which the soluble organic components are decomposed into CO<sub>2</sub>, H<sub>2</sub>, NH<sub>3</sub>, and organic acids in the presence of facultative bacteria. The third phase is acetogenesis, or the initial methanogenic phase, in which the organic acids produced during the second phase are converted into acetic acid, formic acid, alcohols, H<sub>2</sub>, and CO<sub>2</sub> by anaerobic bacteria. In the final phase, methanogenesis, or the stable methanogenic phase, the methanogenic bacteria consume the product of the third phase and produces primarily CH<sub>4</sub> and CO<sub>2</sub>, as well as other trace gases in a smaller amount (Marion et al., 2008; Daniel et al., 1993; Noor et al., 2013). Gas flow can be explained by the percentage of gas composition as Figure 2, which describes the four phases in the landfill (Noor et al., 2013; Chai et al., 2016).

This research is divided into three main sections. The first section describes the estimation model of methane generation in landfill gas. In the second part, we detail computer simulations of landfill gas through mathematical and numerical methods which summarize the usages of each model and compare them to published research. In the last

section, we present applications of the model in real-world problems.

## II. MODELING FOR LANDFILL GAS MODELING FOR LANDFILL GAS

There have been many types of research on models for landfill. In this part, we collect and explain the models for landfill gas, including techniques to find a solution for each condition. Landfill models can be divided into many fields, such as mathematical models, which use mathematical and numerical techniques to show results. Computer simulation is another technique widely used to describe landfill gas and transition.

### A. Estimation of methane generation in landfill

Most research on landfill has studied landfill gas emission, especially methane, with some research summarizing models to estimate methane emission from landfill. In order to estimate landfill gas generation, several studies have been undertaken to investigate and compare. Some of the most widely used models are described in Table 1 (Nadaletti et al, 2015; Das et al, 2016; Kumar et al., 2017; Majdinasab et al, 2017; Vu et al, 2017). Most models were based on the first-order decay (Monod first-order kinetic) model, which involves a linear relationship of the maximum gas generation potential per waste weight unit, as well as an exponential relationship of the waste degradation rate and time. The zero-order model gives significant inaccurate outcomes (Kumar et al., 2017). Following the rapid increase in world population and unprecedented urbanization, waste

All models were modified for the specific area with a clear reference to assignment and source of parameters. First-order decay (FOD) for different climate conditions, parameter  $k$ , and  $L_0$  are different by technique. Sometimes, regression analysis, curve fitting or precipitation-based empirical model are provided for. Moreover, it depends on waste composition or experimental work (Majdinasab et al, 2017). It leads to results fitted well to the actual data or outputs of underestimated methane generation. Therefore, determination of parameters affects results accuracy. The outputs of four mathematical models (TNO, Afvalzorg, LandGEM, and EPER Germany), for example, diverge from each other with increasing time (Das et al, 2016). The advantages and disadvantages, including the assumption of 13 models (IPCC, EPER Germany, SWANA zero-order, SWANA first order, LandGEM, TNO, GasSim, EPER France, Afvalzorg, LFGGEN, Mexico, Halvadakis, and Numerical models) are provided to summarize the differences with each other (Majdinasab et al, 2017). Table 1 shows the model widely used to estimate methane generation in the landfill.

TABLE I. METHANE EMISSION MODELS.

Model name	Formula	Model description	Advantages - Disadvantages
TNO (Renou et al., 2008; Das et al, 2016; Kumar et al., 2017, Majdinasab et al, 2017;, Oonk and Boom,1995; Scharff and Jacobs, 2006)	$\alpha_t = \zeta \times 1.87 \times A \times C_0 \times k_1 \times e^{-k_1 t}$ <p>where</p> $\alpha_t = \text{landfill gas production at a given time}$ $(\text{m}^3 \text{ year}^{-1})$ $\zeta = \text{dissimilation factor, 0.58}$ $1.87 = \text{conversion factor (m}^3)$ $A = \text{amount of waste in place (Mg)}$ $C_0 = \text{amount of organic carbon in waste}$ $(\text{kgC Mg}^{-1})$ $k_1 = \text{degradation rate constant, 0.094 (year}^{-1})$ $t = \text{time elapsed since depositing (year)}$	First-order model with parameters based on real data of landfill gas generation in the Netherlands.	<p>Advantages: Direct estimation of methane and landfill gas.</p> <p>Disadvantages: Information on organic components of waste is not available.</p>
Afvalzorg (Das et al, 2016; Kumar et al., 2017, Majdinasab et al, 2017; Oonk and Boom,1995; Scharff and Jacobs, 2006; Scharff and Jacobs, 2006; IPCC, 2006)	$\alpha_t = \zeta \times \sum_{i=1}^3 c \times A \times C_0 \times k_{1,i} \times e^{-k_{1,i} t}$ <p>where</p> $\alpha_t = \text{landfill gas production at a given time}$ $(\text{m}^3 \text{ year}^{-1})$ $\zeta = \text{dissimilation factor}$ $i = \text{waste fraction with degradation rate } k_{1,i}$ $C = \text{conversion factor (m}^3 \text{ kg}^{-1})$ $A = \text{amount of waste (tons)}$ $C_0 = \text{amount of organic matter (kg tons}^{-1})$ $k_{1,i} = \text{degradation rate constant of fraction } i$ $(\text{year}^{-1})$ $t = \text{time elapsed since depositing (year)}$	<p>First-order, multi-phase model based on waste characteristics in the Netherlands.</p> <p>Waste is classified into three categories in terms of the degradation rate.</p>	<p>Advantages: Freeware model available on demand.</p> <p>Disadvantages: Organic matter or carbon content data were not available for all waste categories.</p>
LandGEM (Das et al, 2016; Majdinasab et al, 2017; Oonk and Boom,1995; Scharff and Jacobs, 2006)	$Q_{CH_4} = \sum_{i=1}^n k \times L_0 \times M_i \times e^{-k t_i}$ <p>where</p> $Q_{CH_4} = \text{methane emission rate (m}^3)$ $k = \text{methane generation constant (year}^{-1})$ $L_0 = \text{methane generation potential}$ $(\text{m}^3 \text{ CH}_4 \text{ Mg Waste}^{-1})$ $M_i = \text{mass of waste in } i^{\text{th}} \text{ section (Mg)}$ $t_i = \text{age of the } i^{\text{th}} \text{ increment or section (year)}$	First-order model based on waste composition in the US. This model uses a first-order decay rate equation to calculate landfill gas generation.	<p>Advantages: User-friendly in a spreadsheet environment.</p> <p>Disadvantages: Confusing and complicated mathematics. Inaccurate assumptions about some variables can result in large errors.</p>

เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้งานเพื่อการศึกษาเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า  
ไม่ว่ากรณีใดๆ ทั้งสิ้น อีกทั้งห้ามมิให้ตัดแปลงเนื้อหา และต้องอ้างอิงถึงเจ้าของเอกสารทุกครั้งที่มีการนำไปใช้

TABLE II. SUMMARY OF RESEARCH ON “COMPUTER SIMULATION OF GAS GENERATION AND TRANSPORT IN LANDFILLS”

Authors	Model's Name	Technique	Finding
Hashemi et al. (2002)	Computer simulation of gas generation and transport in landfills I: quasi-steady-state condition	Analytical analysis and numerical computation	The model is utilized for investigating the gas generation and transport in a model landfill and the effect of various parameters.
Sanchez et al. (2006)	Computer simulation of gas generation and transport in landfills II: Dynamic conditions	Analytical analysis and numerical computation	The comparison of the model's predictions with experimental data indicates the potential of the model for predicting the dynamic behavior of large landfills
Sanchez et al. (2007)	Computer simulation of gas generation and transport in landfills. III: Development of landfills' optimal model	Analytical analysis, numerical simulation and optimization process (genetic algorithm)	The computations are carried out highly efficiently and in a reasonable time, even if one must determine the optimal values of thousands of parameters.
Sanchez et al. (2010)	Computer simulation of gas generation and transport in landfills. IV: Modeling of liquid-gas flow	Analytical analysis and numerical simulation	The results include the flow of leachate and landfill gas.
Li et al. (2011)	Computer simulation of gas generation and transport in landfills. V: Use of artificial neural network and genetic algorithm for short- and long-term forecasting and planning	Artificial neural network (ANN) and genetic algorithm	The results conclude that this model is a powerful approach for developing realistic models of landfills which can be used for making both short- and long-term predictions and planning.
Li et al. (2012)	Computer simulation of gas generation and transport in landfills VI: Dynamic updating of the model using the ensemble Kalman filter	Genetic algorithm and sequential Gaussian simulation (Ensemble Kalman Filter: EnKF)	The results demonstrate the effectiveness and applicability of EnKF updating.

Landfill gas generation rates are currently estimated by mathematical models which depend on each input parameter for each model. Among the models widely used are TNO, Afvalzorg, LandGEM, EPER Germany, and IPCC; their formulas are shown in Table 1. The first three models are first-order models, whereas the last two models are zero-order models. The TNO model uses parameters based on real data of landfill gas generation. The model exists itself as the formula. Afvalzorg is also a first-order multiphase model which looks similar to the TNO-model except for the conversion factor. This model is based on waste characteristics in the Netherlands, and waste is classified into three categories in terms of degradation rate. In addition, it is a freeware model. LandGEM is a model based on waste composition in the US. It uses confusing and complicated mathematics. The model EPER Germany considers the proportion of degradable carbon and waste amount, while IPCC is a model based on degradable organic carbon and waste disposed of, which accommodates four

different climate regions (Renou et al., 2008; Das et al, 2016; Kumar et al., 2017; Majdinasab et al, 2017; Vu et al, 2017; Oonk and Boom, 1995; Scharff and Jacobs, 2006; IPCC, 2006; Tozlu et al., 2016; Mmerekki, 2008; Thompson et al., 2009)

### B. Computer simulations of landfill gas

Much research has studied computer simulations based on mathematical models of landfill gas. An example of interesting research is a series of “Computer simulation of gas generation and transport in landfills”, which consists of six research papers. Firstly, the model entitled “Quasi-steady-state condition”, which is a three-dimensional model for a four-component gas mixture, takes into account the effect of heterogeneity in the distribution of the permeability and porosity in a landfill. Non-linear equations of mass transport and reaction are solved by a novel iterative method (Hashemi et al., 2002). Secondly, the model considers

dynamic conditions by the biodegradation of wastes and transportation. The model is utilized for investigating the dynamic behaviour of a landfill, and in particular pressure build-up, under a variety of conditions. In addition, comparison of the model's predictions with experimental data for a particular landfill indicates the potential of the model for predicting the dynamic behaviour of large landfills (Sanchez et al., 2006).

Thirdly, the problem of the development of optimal model for landfill is addressed by formulating it as one of optimization, whereby the optimal spatial distributions of the porosity, permeability, tortuosity factor, and the total potential of various types of wastes for producing the gases in a landfill are determined, given some limited experimental data for a property of the landfill, such as the amount of methane which is extracted from it over a period of time. The numerical simulator is coupled to the genetic algorithm in order to optimize the parameter space that characterizes the landfill's morphology and the reactive properties of the wastes (Sanchez et al., 2007). The fourth model, entitled "Modeling of liquid-gas flow", is based on a general model of biodegradation (Richardson equation). It demonstrates the strong effect of the heterogeneities of landfill represented by the spatial distribution of the local porosities, as well as an anisotropic distribution of the local permeability on the behavior of a landfill, and the pressure buildup in it (Sanchez et al., 2010). The next model, named "Use of an artificial neural network and the genetic algorithm for short- and long- term forecasting and planning", develops an artificial neural network (ANN) in order to make accurate short-term predictions for several important quantities in a large landfill, including the temperature and gas concentrations; CH<sub>4</sub>, CO<sub>2</sub>, and O<sub>2</sub> (Li et al., 2011). The last model of this series, "Dynamic updating of the model using the ensemble Kalman filter", is based on a combination of the genetic algorithm (GA) and the ensemble Kalman filter (EnKF), in order to generate and update the landfill model (Li et al., 2012). All models were developed for each condition, and the updated models are complex and use higher techniques, as Table 2.

Next, other research has been interested in landfill gas model simulation. Feng (2015a) presented a two – dimensional gas flow model to predict the distribution of gas pressure, using the CH<sub>4</sub> emission flux through partial differential equation with analytical and numerical solutions. This model is indicative of the flow towards a combined extraction system of vertical wells and horizontal gravel-filled trenches.

Moreover, the model has a horizontal layered structure to accommodate anisotropy of municipal solid waste (MSW) and vertical variations in both gas generation rate and permeability. These results provide helpful guidelines to landfill engineers in designing an LFG control system. It can be used to properly describe the gas flow towards a

combined extraction system of vertical wells and horizontal drains in landfills (Feng et al., 2015a). In the same year, this work was improved by developing the previous model for different conditions to enable the study of the gas pressure distribution, well pressure, and recovery efficiency in layered landfills with horizontal wells. A horizontal layered structure is used to accommodate the non-homogeneity of various municipal solid waste aspects with respect to depth, including gas generation, permeability, and temperature. The solution was verified against another analytical solution and numerical simulation. Moreover, a sensitivity analysis of single-well model parameters was performed to optimize a double-well system. The results showed that a landfill with horizontal collection systems cannot be assumed to be one dimensional with increasing well spacing (Feng et al., 2015b).

A comparative analysis using mathematical modeling and simulation, of different methanol production routes, was performed by considering four biogas sources: landfill, palm oil effluent, corn cobs, and sorghum fermentation. For all cases, an optimization study was performed, with the goal of maximizing the methanol production. The results evidenced that the biogas from palm oil was the most profitable, compared to the other sources. On the other hand, the landfill gas was shown to have a very limited capacity for methanol supply. Finally, the process optimization indicated that the operating conditions must be adjusted with respect to the biogas composition, in order to allow the maximum production (Santos et al., 2018).

A model that estimates methane emissions using ambient air methane measurements obtained on the surface of a landfill was created with the method of genetic algorithm-based optimization, combined with the standard Gaussian dispersion model, and employed to identify locations, as well as emission rates of potential emission sources, throughout a municipal solid waste landfill. Four case studies are employed in order to evaluate the performance of the proposed methodology. Results of the four case studies showed the importance of having an overall coverage of all waste disposal of the landfill when surface concentration measurements are performed (Kormi et al., 2018).

Talaiekhazani et al. (2018) showed dispersion modeling by using the AERMOD View model, which is an atmospheric dispersion modeling system and an integrated system that includes three modules. Firstly, a steady-state dispersion model designed for short-range (up to 50 kilometers) dispersion of air pollutant emissions from sources. Secondly, a meteorological data preprocessor (AERMET) that accepts surface meteorological data and upper air soundings data from on-site instrument towers. It then calculates the atmospheric parameters needed by the dispersion model. Lastly, a terrain preprocessor (AERMAP) whose main purpose is to provide a physical relationship

between terrain features and the behavior of air pollution plumes. AERMOD View needs to be provided with several groups of data, such as wind direction, wind speed, ceiling height, global horizontal radiation, relative humidity, etc. In addition, AERMOD includes PRIME (Plume Rise Model Enhancements), which is an algorithm for modeling the effects of downwash created by the pollution plume flowing over nearby buildings. The results showed dispersion modeling for biogas, methane, carbon dioxide, non-methane organic compounds, and carbon monoxide (Talaiekhazani et al., 2018).

Moreover, a simulation model was created that combines the multicomponent diffusive equation and Darcy's Law with the dual Monod kinetic equation or convection-diffusion model to simulate CH<sub>4</sub> transport oxidation and emission in landfill cover soils. This model describes CH<sub>4</sub>, CO<sub>2</sub>, O<sub>2</sub>, and N<sub>2</sub>. The results show methane emission rate, methane emission, and the relationship of parameters. Additionally, it is a reliable method for the estimation of methane emission from landfill, which provides basic data for the creation of a global CH<sub>4</sub> emission inventory (Bian et al., 2018), as Table 3.

TABLE III. SUMMARY OF OTHER PAPERS ON COMPUTER SIMULATIONS ABOUT LANDFILL GAS

Authors	Model's Name	Technique	Finding
Feng et al. (2015a)	A two-dimensional gas flow model for layered municipal solid waste landfills	Analytical techniques and Eigenfunction expansion	The results provide helpful guidelines to landfill engineers in designing an LFG control system for vertical wells and horizontal drains.
Feng et al. (2015b)	A model for gas pressure in layered landfills with horizontal gas collection systems	Analytical techniques, separation of variable and finite integral transforms	The solution can be used for the verification of more complex models and the preliminary design of a horizontal well system.
Santos et al. (2018)	Simulation and optimization of a methanol synthesis process from different biogas sources	Numerical methods and optimization process	The optimal operating parameters were found to be similar to the observation. They provide a good alternative of controlling methane greenhouse gas emissions from municipal solid waste.
Kormi et al. (2011)	Estimation of fugitive landfill methane emissions using surface emission monitoring and genetic algorithms optimization	Genetic algorithms and standard Gaussian dispersion model	The proposed approach enables estimation of landfill methane emissions and localization of major emission hotspots in the studied landfills.
Talaiekhazani et al. (2012)	Gaseous emissions of landfill and modeling of their dispersion in the atmosphere of Shahrekord, Iran	LandGEM and AERMOD view software	Results show modeling of pollutants' distribution into the atmosphere.
Bian et al. (2018b)	A simulation model for estimating methane oxidation and emission from landfill cover soils	Convection – Diffusion model, numerical simulation, and sensitivity analysis	Values of methane emissions predicted using the new model fitted well with the values measured through laboratory experiments.

All of the above models explained gas in landfill using different techniques and assumptions. We can summarize these techniques with machine learning, such as genetic algorithm, numerical method, or sensitivity analysis, which give good results. Moreover, some researches use efficient software, such as AERMOD, which is an interesting method, since it is an atmospheric dispersion modeling system and an integrated system.

### III. APPLICATIONS

For methane emission models, there are several models which are comfortable to use. When using a model, the user

ought to consider the parameters and selection of fitness model. Thompson et al. (2009) compare modeled methane generation to methane generation recovery rates for a statistical sample of landfills. The result showed that LandGEM had the least error and that TNO was a better model than EPER Germany. The outputs also classified the case of the parameter (amount of organic carbon in waste), which gave different errors and correlations (Thompson et al., 2009). Vu (2017) also compared CH<sub>4</sub> estimations from landfill gas models with actual data. In particular, LandGEM was the best fit model, and Afvalzorg gave a lower percentage error than IPCC for all cases. Moreover,

parameters  $k$  and  $L_0$  were changed for each model again. It can be concluded that all landfill does not have to use the same values of parameters. The optimal parameters depend on actual data (Vu et al, 2017). To use a model for the application, the user should test data to look for the most suitable model, including parameter optimization.

$CH_4$  generation variables, such as methane generation rate constant ( $k$ ) and generation potential ( $L_0$ ), are important factors for several models; Table 4 summarizes these parameters and methods used for estimation. The methods for the parameter are estimated by optimization techniques like curve fitting, laboratory experiments, and the linear regression model.

TABLE IV. SUMMARY OF OTHER PAPERS ON COMPUTER SIMULATIONS ABOUT LANDFILL GAS

Authors	Vu et al. (2017)	Fei et al. (2016)	Das et al. (2016)	Wang et al. (2015)	Mou et al. (2015)	Amini (2013)
<b>k min</b>	0.010	0.180	0.030	0.090	0.013	0.040
<b>k max</b>	0.048	5.66	0.080	0.120	0.190	0.090
<b><math>L_0</math> min</b>	44	88	34	55	8	93
<b><math>L_0</math> max</b>	100	98	48	100	107	144
<b>Method</b>	Curve fitting by minimizing the residual sum of squares	Laboratory experiments and landfills	Undefined	Minimizing the residual sum of squares	Experimental work	Curve fitting and linear regression

Computer simulation, as shown in section 2.2, including the application of each model, which is a helpful guideline for the reader to design models for landfill by experimental data. Studying landfill is run on a very extensive scale, particularly research on landfill gas, which gives a great advantage for alternative energy as power generation.

#### IV. CONCLUSION

This paper presents a comprehensive review of different models for landfill gas emission, especially models of methane emission. The most popular models (TNO, Afvalzorg, EPER Germany, LandGEM, and IPCC models) were summarized in order to describe the advantages, disadvantages, and parameters of each. It also discussed computer simulation models which formed six parts of research in the series “Computer simulation of gas generation, and transport in landfills” using a three dimensional model with complex techniques, such as artificial neural network and genetic algorithm. Other models were also supported for computer simulation models with different techniques. In addition, the application section recommended how to find optimal parameters and methods for a landfill.

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เอกสารนี้เป็นเอกสารที่สงวนไว้สำหรับการใช้งานเพื่อการศึกษาเท่านั้น ไม่อนุญาตให้นำไปใช้ประโยชน์ด้านการค้า  
ไม่ว่ากรณีใดๆ ทั้งสิ้น อีกทั้งห้ามมิให้ดัดแปลงเนื้อหา และต้องอ้างอิงถึงเจ้าของเอกสารทุกครั้งที่มีการนำไปใช้