Simplex-centroid mixture for Municipal Solid Waste Treatment Optimisation

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Abstract. A model describing the relationship between waste treatment method and greenhouse gases (GHGs) emission is proposed in this study. Three constituents, i.e., composting, reuse and recycle are analysed using extreme vertices mixture design to determine the model. Mixture design enables identifying of optimum combination of each constituent producing the lowest GHGs emission. Emission of greenhouse gases (GHGs) as a regress and were analysed how they change when the amount of waste changes. The result showed that there are four possible models. One best model is chosen for its least standard deviation, lowest P-value and the highest adjusted R² which is $5.764 \times 10^{-3}$, less than 0.005, and 0.9908 respectively. The model describes that lowest GHGs emission can be achieved by maximizing plastic recycle (into flakes), limiting composting and increasing paper, glass and metal reuse. Composting, reuse and recycle is proportional to the GHGs emission individually, while combination of two constituents is inversely proportional to GHGs emission. The lowest GHGs may be emitted from the plant is 0.107 Gg CO₂ equivalent/year with the composition of constituents as followed: 14 % composting, 50 % reuse, and 26 % recycle equals to 1.3 m³, 4.7 m³ and 2.1 m³ waste from each method.

1. Introduction
These Municipal solid waste management (MSWM) has a complex perspective and requires integrated solution. MSWM is unique since it has complexity covering many different individual issues, such as waste flow, related actors, economic aspect for each waste management alternative, and possible adverse environmental impact for each alternative. Furthermore, MSWM constituent i.e. waste generation and economic estimation involve uncertainties [1, 2]. These factors are uncertainties since it derives from other data which is also a sort of estimation such as population distribution and growth, per capita waste generation rates, economies of scale, local labor and equipment prices. Consequently, estimation should be adopted. Since MSWM demands integrated solution, decision analysis is multi-objective [3]. One decision in certain level of MSWM may affect other level. Different conclusion of MSWM problems may be produced depends on the various perspectives and the subjectivity of the decision-maker. Moreover, environmental valuation can be a very subjective area depending on the methodology adopted leading to personal view of the analyst and consequently his own weighted utility function [4]. [5] proposed an approach called average approach to minimizing the subjectivity in environmental valuation.

Mixture design of experiments is used to seek the optimum conditions for a multivariable system. It is an efficient procedure for strategic planning and executing experiments so that the data obtained can be analysed to yield valid and objective conclusions. Initially, mixture design method was used to
create the possible compositions of selected solid feedstock [6]. There are three standard mixture designs i.e. simplex-vertices, simplex-centroid, and extreme vertices designs. Commonly, there are upper and lower bound constraints on the components. In this study, the extreme vertices mixture vertices designs is used because it is the most appropriate for the actual conditions. The study aims to determine the combination of different waste treatment constituents to reduce GHGs emission from waste sector. First, the waste volume and GHGs reduction potentials in the study area were investigated. Then, the combination of each constituent were evaluated, and the composition of the mixed waste treatment was optimised using response surface methodology.

### Table 1. Typical waste composition in Mataram City

| Waste type     | Percentage |
|----------------|------------|
| Food waste     | 16.08 %    |
| Yard waste     | 45.81 %    |
| Woody waste    | 3.14 %     |
| Plastics       | 17.31 %    |
| Paper          | 11.04 %    |
| Glass          | 0.81 %     |
| Metal          | 0.04 %     |
| Rubber         | 0.89 %     |
| Nappies        | 1.03 %     |
| Others         | 3.85 %     |

### Table 2. Typical waste recovery factor in Mataram City

| Waste type | Recovery Factor |
|------------|-----------------|
| Plastics   | 0.40            |
| Paper      | 0.11            |
| Glass      | 0.49            |
| Metal      | 0.83            |

2. Research methodology

2.1 Waste reduction

Waste generation is measured for 7 days using Load-count Analysis as proposed by [7] by counting the total number of dump trucks entering the landfill each day as described in Equation 1.

\[ V_{tot} = V_i \times n \]

where \( V_{tot} \) is total volume of waste, \( V_i \) is waste volume per truck and \( n \) is the number of trucks. Total volume of waste transported to the landfill is calculated because the landfill is not equipped with weighing bridge. Measurement was conducted in 12 transfer points in Kecamatan Sandubaya from 7 am until 11 am and from 3 pm until 4 pm. Waste volume is calculated based on the typical waste composition in Mataram City [8]. The amount of waste potential for treatment is calculated based on the maximum capacity of composting centre and waste treatment plant shown by Table 1. However, the amount of waste potentials from treatment is determined also by recovery factor in site using Equation 2.

\[ V_r = V_i \times Rf_i \]

where \( V_r \) is waste reduction (m³), \( V_i \) is waste volume (m³) and \( Rf_i \) is recovery factor of each waste type. Recovery factor is a constant describing the waste percentage potential for waste treatment and Table 2 shows the typical recovery factor in study area.
2.2 Waste emission
Tier 2 proposed by [9] is used to calculate waste emission providing some default values which are not available in the study area because of absence of field measurement and lack of local data. Therefore, some assumptions are set during the study which are:

i. Transfer points collects waste and truck transport them directly to the landfill, so that waste volume remains the same. Waste composition in all transfer points as well as in landfill is the same.

ii. Volume of dump truck is 8 m³ and this volume is used to estimate the total waste transported because there is no weighing bridge either in transfer points or landfill.

iii. Recovery factor is identical for all transfer points which is referred to the standard in Mataram City.

iv. Fuel consumption factor is 3.36 L km⁻¹ for light diesel truck based on GHG Protocol Guide 2002 [10].

v. Fuel consumption for grinding machine is 3 L h⁻¹ with treatment capacity of 400 kg h⁻¹ based on Permen PU No.3/PRT/M/2013 [11].

vi. Shredder capacity is 300 kg h⁻¹ which is its maximum capacity.

2.3 Greenhouse gas emission from fuel combustion
Waste transportation and treatment generates GHG emission sources from fuel combustion in shredder and trucks. Total emission is calculated using Equation 3 and Equation 4 from these activities.

\[
E_{\text{tot}} = \sum_{i} (E_{F_i} \times EF_i)
\]  

(3)

\[
V_{Fi} = CF \times t
\]  

(4)

where \(E_{\text{tot}}\) is total emission (Gg CO₂ equivalent or Gg CO₂ eq), \(E_{F_i}\) is fuel energy (TJ) and \(EF_i\) is emission factor of each waste type (kg TJ⁻¹). Fuel energy of gasoline is 44.8 TJ/liter and diesel gas is 43.3 TJ/liter. Meanwhile, \(V_{Fi}\) is fuel consumption (L), \(CF\) is fuel consumption factor (3 L h⁻¹) and \(t\) is operational time (h). Waste volume and shredder capacity are the factors for operational time as showed in Equation 5.

\[
t = \frac{V_i}{C}
\]  

(5)

where \(t\) is operational time (h), \(V_i\) is waste volume (m³) and \(C\) is shredder capacity (300 kg h⁻¹).

2.4 Emission from composting
GHG emission from composting are methane (CH₄) and nitrous oxide (N₂O) calculated using IPCC method (see Equation 6 and Equation 7).

\[
E_m = \sum_{a} \left( V \times M \times EF \times 10^{-3} - R \right) \times 365 \times 21
\]  

(6)

\[
E_n = \sum_{a} \left( V \times M \times EF \times 10^{-3} - R \right) \times 365 \times 310
\]  

(7)

where \(E_m\) is CH₄ emission in inventory year (Gg CO₂ eq/year), \(E_n\) is total N₂O emission in inventory year (Gg CO₂ eq yr⁻¹), \(V\) is organic waste volume (m³), \(M\) is density (kg m⁻³), \(EF\) is emission factor for composting (g GHG per kg waste treated) and \(R\) is recovery factor. Recovery factor is assumed to be zero since there is no activity to utilize the emission and emission factor for composting is 4 g CH₄ per kg waste treated and 0.24 g N₂O per kg waste treated.

2.5 Determining the best alternative for waste treatment
The experiment mixture design (MD) was used to achieve the optimum composition of the waste treatment for minimum GHGs emission. A typical mixture design DoE involves the following steps [12]:

i. Setting bound restriction lower and upper limit for each constituents differs since current waste composition and waste reduction share varies for each waste type. Total organic waste volume exceeds from the minimum required volume for composting, while inorganic waste volume is below reduction target. Therefore, in this case, lower limit for composting is gained by subtracting maximum anorganic waste volume from waste volume reduction target, while those of anorganic waste is attained by subtracting maximum organic waste volume from waste volume.
reduction target. The upper limit is determined based on the potential anorganic waste in the area of the study.

ii. Selecting a suitable technique of mixture design based on the ranges of the independent variables or bound restrictions.

iii. Determining total value of combination. Total value of combination must be the same for all possible models. In this case, 9.3 m$^3$ is set as the total value attained for 10 % waste reduction target.

iv. Choosing an appropriate model to find the relationship between the responses and the mixture components.

v. Run all the determined experiments designed by the model in consecutive order as accorded to the run numbers.

In this case, a model is constructed to describe the best alternative for waste treatment based on the lowest GHGs emission. Three constituents are set, i.e., composting, reuse and recycling and extreme vertices design has been employed in which each constituent is studied in different volumes based on its lower and upper limit. A total of 16 assays were performed (Table 3).

The regression model equations were fitted to a quadratic expression as follows:

$$ Y_i = \Sigma b_j x_j + \Sigma b_{jk} x_j x_k $$

where $Y$ is the response, $b$ is the constants and $X$ is the independent parameters. Statistical analysis of the model was performed to evaluate the analysis of variance (ANOVA).

3. Data analysis

Waste recording has been conducted for 7 d including weekday and weekend. The result shows that the average waste production in Sandubaya District is 93.5 m$^3$ d$^{-1}$ which equals to 22.472 ton d$^{-1}$. As the waste reduction target is 10 %, 9.3 m$^3$ is set to be the maximum waste reduction volume. This amount requires certain mixed waste volume which is defined as potential waste. Table 3 explain the total volume of mixed waste can be treated to produce waste reduction potentials from each waste type. Totally, the potential waste reduction is 61.19 % that equals to 52.7 m$^3$.

Potential organic waste can be reduced through composting is 49.2 m$^3$ comprising of 11.9 m$^3$ food waste and 37.3 m$^3$ leaves remaining residue of 8.6 m$^3$ d$^{-1}$ transported to landfill. Potential inorganic waste can be treated through reuse and recycle is 8.0 m$^3$ d$^{-1}$ comprising of 6.5 m$^3$ plastic waste, 1.1 m$^3$ paper, 0.4 m$^3$ glass, and 0.036 m$^3$ metal.

After determining the lower and upper limit, the values are fed into software of Design Expert to produce sample points describing the percentage of each waste management constituent based on the GHGs emission in Gg CO2 eq y$^{-1}$ as showed in Table 4. Table 5 shows 16 combinations of three constituents and fuel consumption for waste transportation and waste shredding. Classic statistical test is conducted to review the data validity and to find out the coefficient of the variables in the models afterwards.

| Waste type | Total Volume mixed waste (m$^3$ d$^{-1}$) | Waste reduction potentials (m$^3$ d$^{-1}$) | Percentage (%) |
|------------|------------------------------------------|-------------------------------------------|----------------|
| Plastics   | 93.5 m$^3$                               | 6.5                                       | 6.95           |
| Paper      | 93.5 m$^3$                               | 1.1                                       | 1.17           |
| Glass      | 93.5 m$^3$                               | 0.4                                       | 0.42           |
| Metal      | 93.5 m$^3$                               | 0.03                                      | 0.03           |
| Organic    | 93.5 m$^3$                               | 49.2                                      | 52.62          |
| **Total**  | **52.7**                                 |                                           | **61.19**      |
Table 4. Lower and upper limit for MD.

| Waste type      | Treatment | Lower limit (m$^3$) ($V_{max}$-$V_i$) | Upper limit (m$^3$) |
|-----------------|-----------|-------------------------------------|---------------------|
| Organic         | Composting| 1.3                                 | 9.3 m$^3$           |
| Inorganic       | Reuse     | 0                                   | 8.0 m$^3$           |
| Inorganic       | Recycle   | 0                                   | 6.5 m$^3$           |

3.1 Test of normality

Test of normality was conducted to determine if the data of waste volume is well-modelled by a normal distribution and to compute how likely it is for a random variable underlying the data set to be normally distributed and described using line plots represent the experimental and predicted values. The residual is the difference between the observed and the predicted value from the regression. If the points of the plot are seen closer to the straight line, then the data is normally distributed [13]. Figure 1 shows the normal plot of residuals and it is clearly that the experimental points were reasonably aligned suggesting the normal distribution. The residuals were found dispersed randomly about zero indicating that the errors have a constant variance.

![Fig. 1. Normal Probability Plots of the Residuals for GHGs emission.](image)

3.2 Model fitting and regression analysis

The response data based on the independent variables is recorded in Table 5. All of the independent and response variables were tested to fit in to a linear, quadratic or special cubic model. The coefficient of determination ($R^2$), and the F-test (analysis of variance-ANOVA) were used to verify the quality of the models. The analysis of variance (ANOVA) results indicated that the models are significant, and the system can be described using these models. The predicted values were in agreement with the experimental data (Table 5) indicating that the extreme vertices mixture design (EVMD) is a reliable method for determining the optimum composition of the quadratic model was...
identified as the best suited model for GHGs emission. The high coefficients of determination \( R^2 \) and of adjusted \( R^2 \) and sequentil p-value below 0.005 indicate that the response functions fit the experimental data (Table 6).

Based on 16 iterations, a predicted regression equation representing the model with the significant factors for GHGs emission is generated as followed:

\[
E = 0.22 C + 0.105 Re - 0.11 Rc - 0.03 A - 0.05 B - 0.06 C \tag{9}
\]

Where \( E \) is emission (Gg CO₂ eq), \( C \) is Composting (m³), \( Re \) is Reuse (m³), \( Rc \) is Recycle (m³), \( A \) is Composting – Reuse (m³), \( B \) is Composting – Recycle (m³), and \( C \) is Reuse – Recycle (m³). The interactions amongst the three constituents in the GHGs emission were studied in the 16 assays using an extreme vertices mixture design.

The variation of the GHGs emission using different waste treatment methods is shown in two-dimensional ternary contour plot area graphs (Figure 2). Each constituent is represented in one corner of an equilateral triangle. Each point within this triangle refers to a different volume of constituents in the mixture [14]. Table 7 and Table 8 explains waste volume demand for each constituent to enable the optimum waste treatment in Sandubaya District referring 16 possible models.

**Table 5.** Matrix of the extreme vertices mixture design for GHGs emission.

| Run | Waste Volume (m³ d⁻¹) | Fuel Consumption (L y⁻¹) |
|-----|-----------------------|--------------------------|
|     | Composting (C) | Reuse (Re) | Recycling (Rc) | Diesel | Gasoline |
| 1   | 3.98          | 2.78     | 2.54          | 3.352,0 | 390.87 |
| 2   | 1.30          | 4.66     | 3.34          | 4.542,9 | 390.87 |
| 3   | 2.88          | 5.51     | 0.90          | 6.512,5 | 390.87 |
| 4   | 7.63          | 0.00     | 1.66          | 3.974,7 | 390.87 |
| 5   | 5.95          | 1.73     | 1.62          | 9.574,7 | 390.87 |
| 6   | 5.98          | 0.00     | 3.31          | 6.963,7 | 390.87 |
| 7   | 5.94          | 0.00     | 3.36          | 6.963,7 | 390.87 |
| 8   | 3.04          | 1.63     | 4.63          | 6.512,5 | 390.87 |
| 9   | 9.30          | 0.00     | 0.00          | 9.574,7 | 390.87 |
| 10  | 5.25          | 4.053    | 0.00          | 3.352,0 | 390.87 |
| 11  | 7.58          | 1.713    | 0.00          | 9.574,7 | 390.87 |
| 12  | 5.25          | 4.05     | 0.00          | 3.352,0 | 390.87 |
| 13  | 2.80          | 0.00     | 6.50          | 1.821,6 | 390.87 |
| 14  | 1.30          | 4.66     | 3.34          | 4.542,9 | 390.87 |
| 15  | 1.30          | 1.50     | 6.50          | 1.821,6 | 390.87 |
| 16  | 1.30          | 8.00     | 0.00          | 1.822,8 | 390.87 |

**Table 6.** Statistic Summary of Model

| Source     | SD       | Sequential p-Value | Adj. R² | Predict. R² | Remarks     |
|------------|----------|--------------------|---------|-------------|-------------|
| Linear     | 9.261E-003 | < 0.0001         | 0.9895  | 0.9867      |             |
| Quadratic  | 5.764E-003 | < 0.0001         | 0.9908  | 0.9885      | Suggested   |
| Special Cubic | 6.076E-003 | 0.0084          | 0.9927  | 0.9813      |             |
| Cubic      | 5.818E-003 | 0.9198          | 0.9899  | 0.7487      |             |
Fig. 2. Mixture Surface Plots for the GHGs Emission.

Table 7. Volume Waste Demand for Each Constituent for 1 m$^3$ Waste Treatment

| Treatment       | Waste type              | Demand (m$^3$) |
|-----------------|-------------------------|----------------|
| Composting (C)  | Leaves and food         | 1.9            |
| Reuse (Re)      | Plastic, paper, metal   | 11.7           |
| Recycle (Rc)    | Plastic                 | 14.4           |

Table 8. Required total mixed waste for each constituent

| n$^\text{th}$ | Waste Volume (m$^3$ d$^{-1}$) | Mixed Waste Volume (m$^3$ d$^{-1}$) |
|--------------|--------------------------------|-----------------------------------|
|              | $C$ | $Re$ | $Rc$ | $C$ | $Re$ | $Rc$ | Total       |
| 1            | 3.98 | 2.78 | 2.54 | 7.50 | 31.6 | 36.51 | 36.5       |
| 2            | 1.30 | 4.66 | 3.34 | 2.50 | 52.8 | 48.02 | 52.8       |
| 3            | 2.88 | 5.51 | 0.90 | 5.50 | 62.6 | 12.93 | 62.6       |
| 4            | 7.63 | 0.00 | 1.66 | 14.50 | 0.00 | 23.93 | 23.9       |
| 5            | 5.95 | 1.73 | 1.62 | 11.30 | 19.6 | 23.26 | 23.3       |
| 6            | 5.98 | 0.00 | 3.31 | 11.30 | 0.00 | 47.64 | 47.6       |
| 7            | 5.94 | 0.00 | 3.36 | 11.30 | 0.00 | 48.22 | 48.2       |
| 8            | 3.04 | 1.63 | 4.63 | 5.80 | 18.50 | 66.55 | 66.5       |
| 9            | 9.30 | 0.00 | 0.00 | 17.60 | 0.00 | 0.00   | 17.6       |
| 10           | 5.25 | 4.05 | 0.00 | 10.00 | 46.0 | 0.00   | 46.0       |
| 11           | 7.58 | 1.71 | 0.00 | 14.40 | 19.4 | 0.00   | 19.4       |
| 12           | 5.25 | 4.05 | 0.00 | 10.00 | 46.0 | 0.00   | 46.0       |
| 13           | 2.80 | 0.00 | 6.50 | 5.30 | 0.00 | 93.39 | 93.4       |
| 14           | 1.30 | 4.66 | 3.34 | 2.50 | 52.8 | 48.02 | 52.8       |
| 15           | 1.30 | 1.50 | 6.50 | 2.50 | 17.0 | 93.39 | 93.4       |
| 16           | 1.30 | 8.00 | 0.00 | 2.50 | 90.70 | 0.00   | 90.7       |

4. Conclusion
Design of Experiment (DoE) is used in the study to determine the best alternative for solid waste management based on its three constituents i.e. composting, reuse and recycling. The analysis comes to the result as followed:
i. Total waste generation in Sandubaya District is 93 m$^3$ d$^{-1}$ collected and transported to 13 transfer points. Waste volume potentials for waste treatment is 57.33 m$^3$ d$^{-1}$ (61.3 % of total waste) consisting of 49.3 m$^3$ d$^{-1}$ organic waste and 8 m$^3$ d$^{-1}$ inorganic waste.

ii. There are 16 iterations to find out the best model. It is concluded that by optimizing composting lead s to high GHGs emission accounting to 0.227 Gg CO$_2$eq y$^{-1}$. The optimal combination of three constituents for the lowest GHGs emission production is 1.3 m$^3$ d$^{-1}$ composting, 4.7 m$^3$ d$^{-1}$ reuse and 3.2 m$^3$ d$^{-1}$ recycle which can decrease GHGs emission up to 0.2 Gg CO$_2$eq y$^{-1}$.

iii. The next research will be the observation for the best models based on technical and economical aspect using the same waste treatment constituents. The results will be the best model of waste treatment representing the most efficient in land demand, operational cost and GHGs emission.

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