Method Article

Development of a dynamic optimization framework for waste management systems

Mohamed Abdallah\textsuperscript{a,}\textsuperscript{*}, Sadeque Hamdan\textsuperscript{b}, Ahmad Shabib\textsuperscript{a}

\textsuperscript{a}Department of Civil and Environmental Engineering, University of Sharjah, Sharjah, United Arab Emirates
\textsuperscript{b}Laboratoire Génie Industriel, Université Paris-Saclay, CentraleSupélec, 91190 Gif-sur-Yvette, France

A B S T R A C T

Waste to energy (WTE) technologies have emerged as an alternative solution to municipal solid waste management. WTE systems provide major environmental and economic benefits by converting waste into accessible energy, as part of an integrated solid waste management (ISWM) strategy. However, previous studies showed that establishing an ISWM strategy based on a single type of WTE systems does not necessarily realize maximum benefits. Hence, optimizing the selection of WTE systems as part of a hybrid waste management strategy can potentially achieve maximum benefits and minimize negative impacts. However, such task is challenging due to the various alternatives and objectives, particularly those related to the material and energy recovery systems. This article presents the methods used to develop a systematic optimization framework that identifies the most beneficial set of ISWM systems through mathematical modelling. The methods include the procedures of the established framework, including base model computations, as well as the comprehensive modelling and optimization methods.

- The energy recovery, carbon footprint, and financial profitability are computed for selected WTE facilities.
- The multi-objective mathematical programming is solved using the weighted comprehensive criterion method (WCCM).
- The model is implemented in CPLEX software using mathematical programming language (OPL).

© 2021 The Author(s). Published by Elsevier B.V.
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/)

A R T I C L E  I N F O

Method name: Multi-Objective Optimization Model for Integrated Waste Management Strategies
Keywords: Optimization, Mathematical modelling, Energy recovery, Financial feasibility, Carbon Footprint
Article history: Received 15 November 2020; Accepted 27 December 2020; Available online 7 January 2021

DOI of original article: 10.1016/j.jclepro.2020.124714
* Corresponding author.
E-mail address: mabdallah@sharjah.ac.ae (M. Abdallah).
Specifications table

| Subject Area:     | Engineering |
|------------------|-------------|
| More specific subject area: | Solid Waste Management and Operation Research |
| Method name:     | Multi-Objective Optimization Model for Integrated Waste Management Strategies |
| Name and reference of original method: | N/A |
| Resource availability: | https://www.ibm.com/ae-en/analytics/cplex-optimizer |

### Method details

#### Optimization framework

This article presents the methods used to establish the framework of a multi-objective optimization model developed to systematically design an optimal waste to energy (WTE)-based management strategy for a given study area. Fig. 1 shows the optimization framework developed for the model, along with the limitations of various steps. The framework is mainly divided into two parts: model computations as well as modelling and optimization. The model computations include base calculations of energy production, carbon footprint, and financial profitability for various waste materials processed in selected waste management facilities. The modelling and optimization module includes a multi-objective mixed integer linear programming model. The multi-objective formulation is solved using the weighted comprehensive criterion method (WCCM).

#### Model computations

The computations conducted on the optimization model inputs include the energy recovery, greenhouse gas (GHG) emissions, and financial profitability for each waste management facility, namely incinerator, anaerobic digester (AD), and sanitary landfill with gas recovery. The calculation steps, equations, and default values (DV) of these facilities are listed below.

**Incinerator**

1- Calculate the equivalent carbon emissions, $E_{CO_2}$, from incineration processes [10].

$$E_{CO_2} = W_p \times \frac{44}{12} \times \sum (M_i \times dm_i \times CF_i \times FCF_i \times OF_i)$$

Where $E_{CO_2}$ is the total equivalent carbon emissions in a year, Gg CO2-eq/year

$W_p$ is the total mass of waste processed in facility, Gg/year

$M_i$ is the mass fraction of material $i$ in the waste stream

$dm_i$ is the dry matter fraction of waste material $i$ (DVs in Table 1)

$CF_i$ is the fraction of carbon in the dry matter of waste material $i$ (DVs in Table 1)

$FCF_i$ is the fraction of fossil carbon in the total carbon of waste material $i$ (DVs in Table 1)

$OF_i$ is the oxidation factor (DV=1)

2- Calculate the energy produced, $EP$, through incineration.

$$EP = W_d \times \eta \times \sum (M_i \times CV_i)$$

Where $EP$ is the energy production from facility, kWh

$W_d$ is the dry weight of waste processed, kg

$\eta$ is the efficiency of energy conversion within incinerators (DV=0.30)

$M_i$ is the mass fraction of material $i$ in the waste stream

$CV_i$ is the calorific value of material $i$, kWh/kg (DVs in Table 1)

3- Calculate the net present value of the incineration facility.

$$NPV = \sum_i \left\{ \left[ (W_p \times TF) + (EP \times ET) - CAPEX_i - OPEX_i \right] \times (1 + i)^{-t} \right\}$$
Table 1
Stoichiometric parameters, energy content, and DOC values of various waste fractions.

| Parameter | Paper | Plastic | Glass | Wood | Textiles | Organics | Metal | Others |
|-----------|-------|---------|-------|------|----------|----------|-------|--------|
| Stoichiometric parameters | n  | 3.6 | 5.0 | 0.0 | 4.1 | 1.0 | 0.0 | 3.7 | 3.4 |
| | a | 5.8 | 7.1 | 0.0 | 6.1 | 1.7 | 0.0 | 6.4 | 5.6 |
| | b | 2.8 | 1.4 | 0.0 | 2.7 | 0.7 | 0.0 | 1.8 | 2.4 |
| Dry matter fraction (dm) | 0.020 | 0.000 | 0.007 | 0.007 | 0.040 | 0.000 | 0.020 | 0.100 |
| Dry matter carbon fraction (CFi) | 0.46 | 0.75 | 0.00 | 0.50 | 0.50 | 0.38 | 0.00 | 0.03 |
| Fossil carbon fraction (FCFi) | 0.01 | 1.00 | 0.00 | 0.20 | 0.00 | 0.00 | 1.00 | 0.00 |
| Calorific value (Btu/kg) | 14,991 | 30,865 | 0 | 16,094 | 17,857 | 5291 | 661 | 11,464 |
| Degradable organic carbon (DOCi) | 0.40 | – | 0.43 | 0.24 | 0.15 | – | – | – |

* [2]: from a study conducted for the US Department of Health, Education and Welfare on different waste streams, and results were originally reported as percentage of total mass; [9]: from the Intergovernmental Panel on Climate Change (IPCC) guidelines for national greenhouse gas inventories; [8]: compiled from full-scale WTE facilities in China.

Fig. 1. Proposed framework of the multi-objective optimization model.

Where NPV is the net present value, USD

\[ W_p \] is the total mass of waste processed in facility, Gg/year

\[ TF \] is the tipping fee per 1000 ton of waste, USD/Gg

\[ EP \] is the energy production from facility, kWh

\[ ET \] is the electricity tariff, USD/kWh

\[ CAPEX_t \] is the capital investment costs in year \( t \), USD

\[ OPEX_t \] is the operational and maintenance costs in year \( t \), USD

\( i \) is the discount rate (%)

\( t \) is the economic life of the project (year)

Anaerobic digester (AD)

4- Calculate the equivalent carbon emissions, \( E_{CO_2} \), from AD plants, as per tier 2 of the Intergovernmental Panel on Climate Change (IPCC) guidelines [9].

\[
E_{CO_2} = W_p \times EF \times (1 - R) \times GWP
\]  

(4)

Where \( E_{CO_2} \) is the total equivalent carbon emissions in a year, Gg CO\(_2\)-eq/year

\( W_p \) is the total mass of waste processed in facility, Gg/year

\( EF \) is the emission factor, g CH\(_4\)/g waste (DV=0.0008)

\( R \) is the fraction of CH\(_4\) recovered (DV=0.90)
GWP is the global warming potential of methane (DV=28)

5- Calculate the energy produced, EP, through AD based on the general formula of waste materials \(C_nH_{2n}O_{2n}N_C\) (modified from [7,8]).

\[
EP = \sum \left[ \frac{(8 \times n) - (2 \times a) - (4 \times b) - (6 \times c)}{(12.01 \times n) + (1.01 \times a) + (16.00 \times b) + (14.01 \times c)} \right] \times W_d \times EC_{CH_4} \times \eta \tag{5}
\]

Where EP is the energy production from facility, kWh
\(n, a, b,\) and \(c\) are the normalized mole ratio of \(C, H, O,\) and \(N\) in waste material \(i\) (DVs in Table 1)
\(W_d\) is the dry weight of waste processed, kg
EC\(_{CH_4}\) is the energy content of methane, kWh/kg (DV=14.31)
\(\eta\) is the efficiency of energy conversion within AD plants (DV=0.30)

6- Calculate the net present value of the AD plant (similar to Step 3)

**Sanitary landfill with gas recovery**

7- Calculate the equivalent carbon emissions, \(E_{CO_2}\), from landfill, as per tier 2 of the IPCC guidelines [3].

\[
E_{CO_2} = \frac{W_p \times \sum (M_i \times DOC_i) \times DOC_F \times MCF \times F \times \left( \frac{16}{12} \right) \times (1 - R) \times (1 - OX) \times GWP}{10^6} \tag{6}
\]

Where \(E_{CO_2}\) is the total equivalent carbon emissions in a year, Gg CO\(_2\)-eq/year
\(W_p\) is the total mass of waste processed in facility, Gg/year
\(M_i\) is the mass fraction of material \(i\) in the waste stream
DOC\(_i\) is the degradable organic carbon of material \(i\) (DVs in Table 1)
DOC\(_F\) is the fraction DOC dissimilated (DV=0.77)
MCF is the methane correction factor (DV=0.60)
\(F\) is the methane fraction in landfill gas (DV=0.50)
\(R\) is the fraction of methane recovered (DV=0.70)
OX is the oxidation factor (DV=0)
GWP is the global warming potential of methane (DV=28)

8- Calculate the energy produced, \(EP\), through landfill gas recovery.

\[
EP = E_{CH_4} \times R \times EC_{CH_4} \times 10^6 \times \eta \tag{7}
\]

Where \(EP\) is the energy production from facility, kWh
\(E_{CH_4}\) is the total methane emissions in a year, Gg CH\(_4\)/year (using Eq. (6) excluding the \((1-R)\) and \(GWP\) terms).
\(R\) is the fraction of methane recovered (DV=0.70)
EC\(_{CH_4}\) is the energy content of methane, kWh/kg (DV=14.31)
\(\eta\) is the efficiency of energy conversion in landfill gas combustion facilities (DV=0.30)

9- Calculate the net present value of the sanitary landfill site (similar to Step 3)

**Modelling and optimization**

The mixed integer linear programming model formulated in Abdallah et al. [1] is solved using the WCCM. The WCCM requires dealing with the model’s objective functions individually and then developing a new objective function that combines all objectives [4–6]. Fig. 2 illustrates the process of applying WCCM for the waste management strategies. The process starts by solving the mathematical model for each objective function separately subject to all the constraints (Steps 1, 2 and 3 in Fig. 2).
Table 2
Input data needed to run the optimization model.

| Code input      | Description                                                                                                                                 |
|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Demand          | The quantities of waste available from each material and each year. The input data should be organized in a matrix form, where the rows are the materials (food, recyclable and non-recyclable) and the columns are the years. |
| CO2             | The carbon footprint equivalent of each material resulting from each strategy calculated using Eqs. (1), (4), and (6). The input data should be organized in a matrix form, where the rows are the materials (food, recyclable and non-recyclable) and the columns are the strategies (anaerobic digester, incinerator, and landfill). |
| CO2_2           | The carbon footprint equivalent of digestates and ashes resulting from each strategy calculated using Eqs. (1), (4), and (6). The input data should be organized in a matrix form, where the first row is for the digestate and the second row is for the ashes. The columns represent the strategies (anaerobic digester, incinerator, and landfill). |
| Energy          | The energy recovery of each material resulting from each strategy calculated using Eqs. (2), (5), and (7). The input data should be organized in a matrix form, where the rows are the materials (food, recyclable and non-recyclable) and the columns are the strategies (anaerobic digester, incinerator, and landfill). |
| Energy_2        | The energy recovery of digestates and ashes resulting from each strategy calculated using Eqs. (2), (5), and (7). The input data should be organized in a matrix form, where the first row is for the digestate and the second row is for the ashes. The columns represent the strategies (anaerobic digester, incinerator, and landfill). |
| CAPEX           | The CAPEX value of each material under each strategy calculated using Eq. (3). The input data should be organized in a matrix form, where the rows are the materials (food, recyclable and non-recyclable) and the columns are the strategies (anaerobic digester, incinerator, and landfill). |
| CAPEX_2         | The CAPEX value for digestates and ashes using different strategies calculated using Eq. (3). The input data should be organized in a matrix form, where the first row is for the digestate and the second row is for the ashes. The columns represent the strategies (anaerobic digester, incinerator, and landfill). |
| Profit_S1       | The NPV profit for each material in each year calculated using Eq. (3). The input data should be organized in a matrix form, where the rows are the materials (food, recyclable and non-recyclable) and the columns are the years. S1, S2, S3 denote the anaerobic digester, incinerator, and landfill. |
| Profit_S2       | The NPV profit of digestates for each strategy in each year calculated using Eq. (3). The input data should be organized in a matrix form, where the rows are the strategies and the columns are the years. |
| Profit_S3       | The NPV profit of digestates for each strategy in each year calculated using Eq. (3). The input data should be organized in a matrix form, where the rows are the strategies and the columns are the years. |
| Profit_Dig      | The NPV profit of digestates for each strategy in each year calculated using Eq. (3). The input data should be organized in a matrix form, where the rows are the strategies and the columns are the years. |
| Profit_Ash      | The NPV profit of ashes in each year calculated using Eq. (3). The input data should be organized in a matrix form, where the rows are the strategies and the columns are the years. |
| A1, A2, A3      | A single value used in the multi-objective code (WCCM.mod) representing the importance weight of the profit, carbon footprint and energy recovery objective function, respectively. |
| Popt            | A single value used in the multi-objective code (WCCM.mod). It represents the optimal value from solving the problem for maximization of the profit objective only (Profit.mod). |
| Eopt            | A single value used in the multi-objective code (WCCM.mod). It represents the optimal value from solving the problem for maximization of the energy recovery objective only (Energy.mod). |
| Copt            | A single value used in the multi-objective code (WCCM.mod). It represents the optimal value from solving the problem for minimization of the carbon footprint objective only (Emission.mod). |

Fig. 2. Multi-objective optimization framework.
Next, based on the expert opinions, the importance weights of each objective function are determined using Fuzzy Analytical Hierarchy Process (AHP).

The mathematical model and the solution approach for the multi-objective formulation, the WCCM, have been implemented using the optimization programming language (OPL) in the CPLEX software (by IBM). The code files are available in the Supplementary Files. Table 2 describes the input data needed to run the model.

The code files (Emission.mod, Energy.mod, and Profit.mod) should be run first in any sequence to obtain the optimal objective value for each single objective function. Then the code file (WCCM.mod) should be run to obtain the multi-objective solution.

Conclusion

In this paper, the methodology used in the multi-objective waste management optimization problem was presented. The equations used in obtaining the input data of the mathematical model were detailed. Additionally, all software codes used to solve the formulated mathematical model were provided and thoroughly described. The codes are based on the optimization programming language of CPLEX. The presented model can be effectively utilized to generate a comprehensive waste management master plan that satisfies the specific goals of decision makers. For future research work, the analysis framework and codes can be modified to account for more features and objectives. Moreover, evolutionary methods, such as genetic algorithms, can be utilized to effectively solve the optimization problem.

Declaration of Competing Interest

The Authors confirm that there are no conflicts of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi: 10.1016/j.mex.2020.101203.

References

[1] M. Abdallah, S. Hamdan, A. Shabib, A multi-objective optimization model for strategic waste management master plans, J. Clean. Prod. 124714 (2020) 1–16, doi:10.1016/j.jclepro.2020.124714.
[2] H.A. Arafat, K. Jijakli, Modeling and comparative assessment of municipal solid waste gasification for energy production, Waste Manage. 33 (2013) 1704–1713, doi:10.1016/j.wasman.2013.04.008.
[3] J.B. Coburn, K. Pingoud, G. Thorsen, F. Wagner, Solid waste disposal, in: Proceedings of the IPCC Guidelines for National Greenhouse Gas Inventories Volume 5, Waste, 2006.
[4] S. Hamdan, A. Cheaitou, Dynamic green supplier selection and order allocation with quantity discounts and varying supplier availability, Comput. Ind. Eng. 110 (2017) 573–589, doi:10.1016/j.cie.2017.03.028.
[5] S. Hamdan, A. Cheaitou, O. Jouini, Z. Jemai, I. Alyouf, M. Bettayeb, An environmental air traffic flow management model, in: Proceedings of the 8th International Conference on Modeling, Simulation, and Applied Optimization (ICMSAO), Bahrain, IEEE, 2019.
[6] R.T. Marler, J.S. Arora, Survey of multi-objective optimization methods for engineering, Struct. Multidiscip. Optim. 26 (2004) 369–395, doi:10.1007/s00158-003-0368-6.
[7] A.S.O. Ogunjuyigbe, T.R. Ayodele, M.A. Alao, Electricity generation from municipal solid waste in some selected cities of Nigeria: an assessment of feasibility, potential and technologies, Renew. Sustain. Energy Rev. 80 (2017) 145–162, doi:10.1016/j.rser.2017.05.177.
[8] O.K.M. Ouda, R. Al-Waked, S. Raza, Potential value of waste-to-energy facility in Riyadh city, Saudi Arabia, in: Proceedings of the 8th Jordanian International Mechanical Engineering Conference, 2014.
[9] Pipatti, R., Alves, J.W.S., Gao, Q., Cabrera, C.L., Mareckova, K., Oonk, H., Scheehle, E., Sharma, C., Smith, A., Svardal, P., Yamada, M., 2006. Chapter 4 - Biological treatment of solid, 2006 IPCC Guidel. Natl. Greenh. Gas Invent. 4.4.1–4.4.8.
[10] M.J. Rogoff, F. Screve, Introduction and overview, Waste-to-Energy (2011), doi:10.1016/B978-1-4377-7871-7.10001-2.