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Method Article

Development of a dynamic optimization framework for waste management systems

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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).*

A R T I C L E   I N F O
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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].

$$E_{CO_2} = W_p \times \frac{44}{12} \times \sum (M_i \times dm_i \times CF_i \times FCF_i \times OF_i) \quad (1)$$

Where E_{CO2} 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
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.

$$EP = W_d \times \eta \times \sum (M_i \times CV_i) \quad (2)$$

Where *EP* is the energy production from facility, kWh
W_d is the dry weight of waste processed, kg
η 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.

$$NPV = \sum_{1}^{t} \left\{ \left[\left(W_p \times TF \right) + (EP \times ET) - CAPEX_t - OPEX_t \right] \times (1+i)^{-t} \right\} \quad (3)$$

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
	c	0.020	0.000	0.000	0.007	0.040	0.000	0.020	0.100
Dry matter fraction (dm_i)		0.40	–	–	0.43	0.24	0.15	–	–
Dry matter carbon fraction (CF_i)		0.46	0.75	0.00	0.50	0.50	0.38	0.00	0.03
Fossil carbon fraction (FCF_i)		0.01	1.00	0.00	0.00	0.20	0.00	0.00	1.00
Calorific value (Btu/kg)		14,991	30,865	0	16,094	17,857	5291	661	11,464
Degradable organic carbon (DOC_i)		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 orginially 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.

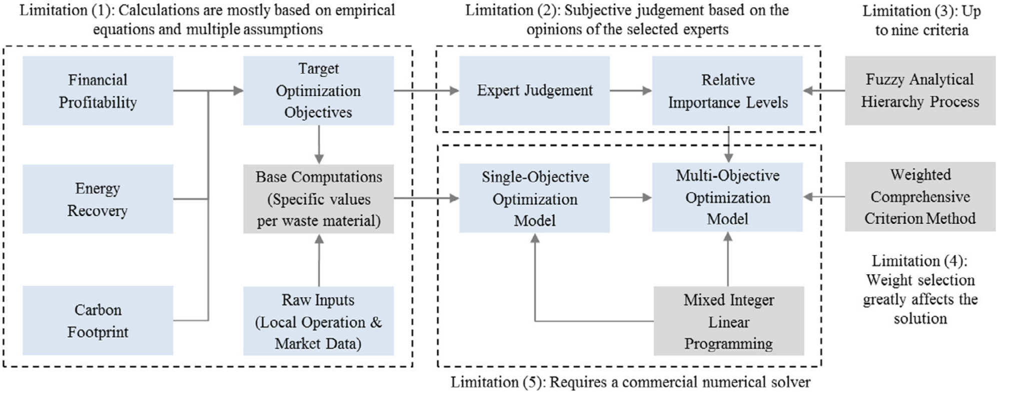

Fig. 1. Proposed framework of the multi-objective optimization model.

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].

$$E_{CO_2} = W_p \times EF \times (1 - R) \times GWP \tag{4}$$

Where E_{CO2} 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 $C_nH_aO_bN_c$ (modified from [7,8]).

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

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_{CH4} is the energy content of methane, kWh/kg (DV=14.31)
η 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].

$$E_{CO_2} = W_p \times \sum (M_i \times DOC_i) \times DOC_F \times MCF \times F \times \left(\frac{16}{12}\right) \times (1 - R) \times (1 - OX) \times GWP \quad (6)$$

Where E_{CO2} 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.

$$EP = E_{CH_4} \times R \times EC_{CH_4} \times 10^6 \times \eta \quad (7)$$

Where *EP* is the energy production from facility, kWh
E_{CH4} 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_{CH4} is the energy content of methane, kWh/kg (DV=14.31)
η 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, Profit_S2, Profit_S3	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_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 one row, where 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).

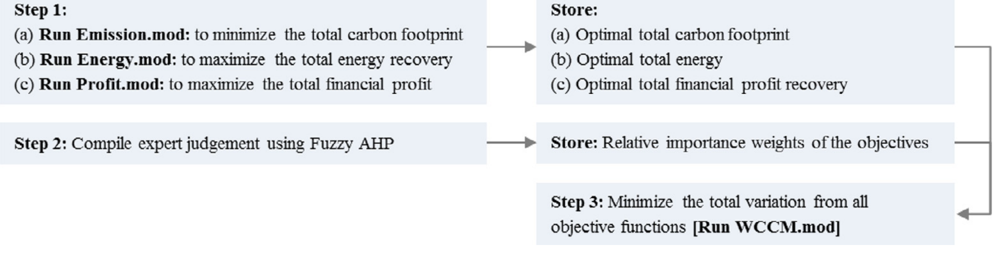

Fig. 2. Multi-objective optimization framework.

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.

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