Mohammadi, Maryam; Jämsä-Jounela, Sirkka-Liisa; Harjunkoski, Iiro

A Multi-Echelon Supply Chain Model for Sustainable Electricity Generation from Municipal Solid Waste

Published in:
IFAC-PapersOnLine

DOI:
10.1016/j.ifacol.2019.06.130

Accepted/In press: 17/01/2019

Document Version
Peer reviewed version

Please cite the original version:
A Multi-Echelon Supply Chain Model for Sustainable Electricity Generation from Municipal Solid Waste


*Research Group of Process Control and Automation, Department of Chemical and Metallurgical Engineering, School of Chemical Engineering, Aalto University, FI-00076 Espoo, Finland
(e-mail: maryam.mohammadi@aalto.fi; sirkka-liisa.jamsa-jounela@aalto.fi)
**ABB Corporate Research Center Germany, Wallstader Str. 59, 68526 Ladenburg, Germany
(e-mail: iiro.harjunkoski@de.abb.com; iiro.harjunkoski@aalto.fi)

Abstract: This paper addresses a mixed integer linear programming model for the optimal utilization of municipal solid waste in a multi-echelon supply chain network. The model focuses on tactical and operational level decisions including the supply, production, and distribution. It aims to maximize the annual net profit by optimizing the choice of waste-to-energy technologies through observing the related capacity and environmental constraints and market demands. The proposed sustainable waste management model not only reduces the burden on the environment, but also optimally distributes the solid waste through the system and converts it into electricity, thus contributing towards energy supply. Sensitivity analyses are conducted to investigate the effects of changes in waste separation rate, energy conversion rate, and energy efficiencies on the system performance and on the environment. The model is solved using GAMS/Cplex.

Keywords: municipal solid waste, waste management, waste-to-energy, sustainability, supply chain management, mixed integer linear programming.

1. INTRODUCTION

Globally, municipal solid waste (MSW) generation rates are rising rapidly. Burying the waste in landfills is not anymore a common waste management solution as it used to be. Currently, the disposal of waste is the last option of the waste management hierarchy. Among the available waste management strategies, waste-to-energy (WtE) has become an effective waste management solution, which provides an ecologically sound and cost-effective solution to both MSW disposal dilemmas and energy demand.

WtE processes recover heat, electricity, biofuels (transportation fuels), synthetic natural gas, and chemicals from non-recyclable and non-reusable waste materials through a variety of processes, including thermochemical, biochemical, and physicochemical conversion techniques. The choice of conversion technology depends on various factors such as type and quality of waste, the physicochemical properties of the waste, capital and operational costs, end-uses of generated products, geographical location, and infrastructure. The three principal methods of conversion technologies include conventional incineration, pyrolysis, and gasification. WtE leads to reducing the cost of waste transportation to landfills often located far away from cities, landfill cost savings, and reducing the demand for lands required for waste disposal.

MSW is considered a suitable source for energy production compared to other waste sources and residue feedstock because of its availability during the year, specified supply locations, and contribution to revenue generation. It can also be stored more efficiently and for longer time-periods, and utilized on demand. The use of MSW as a renewable energy source reduces the world’s dependency on traditional fossil fuels, and contributes to the conservation of natural resources, in addition to decreasing the carbon dioxide (CO₂) emission generated from coal, oil, and natural gas power plants (Pan et al., 2015).

In addition to the economic benefits gained in the waste recovery processes, nowadays, waste management regulations have become stricter regarding protecting the environment by putting pressure on manufacturers producing energy from waste and disposal of end-of-life products in an environmentally sound manner. The traditional solid waste burning in large furnaces with little or no concerns or regulations for air pollution no longer exists. Modern WtE facilities are capable of recovery of the energy contained in the burned waste with the highest efficiency, cleaning the flue gases, and condensing the water vapour. Currently, WtE plants produce less greenhouse gases such as methane (CH₄) compared to the landfills.

WtE can be associated with multiple stages in the integrated supply chain (SC) network as it involves the waste collection, waste separation and pre-treatment, storage, transportation, energy conversion processes, and distribution of products to the end users. In this context, the integrated SC is not anymore the forward SC, but a reverse SC. Although much consideration has been devoted to developing the mathematical models for optimal utilization of MSW in WtE practices, most of these models have considered partial integration of the functions in an SC. Only a few studies focus...
on the optimization of the MSW systems in integrated WtE SC networks. A well-designed integrated SC contributes to the smooth flow of waste among the SC entities, extracting the maximum value from the generated waste, improving responsiveness and increasing the service level, acquiring a better energy efficiency, and lowering the environmental impacts. More detailed information related to the optimization of the entire SC for MSW management can be found in Balaman et al. (2018) and Mohammadi et al. (2018; 2019).

An efficient SC network design for waste management systems is essential as it seeks to find a trade-off between SC costs, diminution of generated waste, and effective utilisation of waste, while considering the environmental impacts. Accordingly, the objective of this work is to combine the essential functions associated with the integrated SC network in WtE systems, which were not taken into account precisely in the previous works, mainly because of the intricacy in the integration of SC fundamentals. For this purpose, a mixed integer linear programming model (MILP) is developed for the optimal planning of WtE processes in a multi-level SC network. An optimal SC plan for this problem determines the efficient flow of waste among the SC entities in order to fulfil the product’s demand, while not exceeding the existing capacity restrictions at all levels of SC network, as well as predetermined emission limits for the road transportation, landfilling, and WtE operations.

2. MATHEMATICAL MODEL FORMULATION

2.1 Problem Statement

This paper presents an SC optimization model for sustainable handling and processing the MSW to generate electricity using WtE technologies. The optimal selection of conversion technologies depends on the distribution of MSW among different levels of the network, electricity demand, and capacity levels for the plants and landfills, as well as existing environmental restrictions for the transportation, landfilling, and operations. Figure 1 shows the WtE SC network under investigation.

The SC network comprises the waste collection points, separation centres, landfills, WtE plants, and consumer locations. Different vehicles with different loading capacities carry out the flow of waste among the entities of the network. It is considered that ownership of the waste SC belongs to the local authorities, and there are not specifically waste buyers and waste suppliers. Thus, separation centres do not make any profit by sending waste to the production facilities. The aim of the proposed model is to maximize the profit of the entire SC network by minimizing the total system cost including collection, separation, landfilling, operation, and transportation costs, and maximizing electricity generation over a finite horizon. Furthermore, the developed model is generic and does not have any limitation to the type of WtE technology.

2.2 Model Formulation

2.2.1 Notation

Indices:
- \( c \) Waste collection point, \( c \in \{1, 2, \ldots, C\} \)
- \( l \) Landfill, \( l \in \{1, 2, \ldots, L\} \)
- \( m \) Municipality, \( m \in \{1, 2, \ldots, M\} \)
- \( p \) Waste processing plant, \( p \in \{1, 2, \ldots, P\} \)
- \( s \) Waste separation centre, \( s \in \{1, 2, \ldots, S\} \)
- \( t \) Time period, \( t \in \{1, 2, \ldots, T\} \)
- \( w \) Waste type, \( w \in \{1, 2, \ldots, W\} \)
- \( v \) Vehicle type, \( v \in \{1, 2, \ldots, V\} \)

Parameters:
- \( A_{\text{wct}} \) Amount of waste type \( w \) accumulated in collection point \( c \) in period \( t \)
- \( A_{\text{CH}_4}^{l}\) Allowed level of \( \text{CH}_4 \) emission for landfill \( l \) in period \( t \)
- \( A_{\text{CO}_2}^{p}\) Allowed level of \( \text{CO}_2 \) emission from WtE operations by plant \( p \) during period \( t \)
- \( A_{\text{CO}_2}^{st}\) Allowed level of \( \text{CO}_2 \) emission from transportation by separation centre \( s \) in period \( t \)
- \( C_{\text{land}}^{lt}\) Landfilling cost in landfill \( l \) in period \( t \)
- \( C_{\text{col}}^{mt}\) Collection cost of waste in municipality \( m \) in period \( t \)
- \( C_{\text{dism}}^{pt}\) Distribution cost of electricity from plant \( p \) to municipality \( m \) in period \( t \)
- \( C_{\text{prod}}^{pt}\) Production cost of electricity in plant \( p \) in period \( t \)
- \( C_{\text{fix}}^{v}\) Separation cost of waste \( w \) in separation centre \( s \) in period \( t \)
- \( C_{\text{var}}^{v}\) Fixed and variable transportation costs for vehicle type \( v \)
- \( D_{\text{ms}}\) Distances from municipality \( m \) to separation centre \( s \)
- \( D_{\text{st}}^{s}\) from separation centre \( s \) to landfill \( l \)
- \( D_{\text{sp}}\) centre \( s \) to plant \( p \)
- \( D_{\text{el}}^{m}\) Demand of electricity in municipality \( m \) in period \( t \)
- \( E_{\text{CO}_2}\) Amount of CO\(_2\) emission per litre of fuel
- \( E_{\text{CO}_2}^{wp}\) Amount of CO\(_2\) emission incurred for processing waste \( w \) in plant \( p \)
- \( E_{\text{CH}_4}\) Amount of CH\(_4\) emission from landfilling per ton of waste

Fig. 1. A schematic representation of the WtE SC network.
\( F_v \) Amount of litre of fuel consumed per kilometre for vehicle type \( v \)

\( LC_{pt} \) Capacity level of landfill \( l \) in period \( t \)

\( PC_{pt} \) Capacity level of plant \( p \) to generate electricity in period \( t \)

\( PC_{row}^{up}, PC_{row}^{lo} \) Lower and upper capacity levels of plant \( p \) to operate the waste \( w \) treatment

\( P_{mt} \) Selling price of electricity in municipality \( m \) in period \( t \)

\( V_C_{v} \) Capacity of vehicle \( v \)

\( \alpha_{wpt} \) Separation factor for waste \( w \) in period \( t \)

\( \gamma_{wpt} \) Conversion factor of waste \( w \) to electricity in plant \( p \)

\( \varphi_{p} \) Energy efficiency percentage of a WtE technology in plant \( p \)

\( \chi_{p} \) Energy loss percentage at electricity grids controlled by plant \( p \)

**Positive variables:**

\( I_{mt} \) Lost demand in municipality \( m \) during period \( t \)

\( q_{lt} \) Quantity of waste transferred to landfill \( l \) in period \( t \)

\( q_{wmnt} \) Quantity of waste \( w \) collected in municipality \( m \) in period \( t \)

\( q_{et} \) Quantity of electricity transferred to municipality \( m \) in period \( t \)

\( q_{pt} \) Quantity of electricity transferred from plant \( p \) to municipality \( m \) in period \( t \)

\( q_{pt} \) Quantity of generated electricity in plant \( p \) during period \( t \)

\( q_{wmsvt} \) Quantity of waste \( w \) distributed from municipality \( m \) to separation centre \( s \) via vehicle type \( v \) in period \( t \)

\( q_{wpt} \) Quantity of waste \( w \) transferred to plant \( p \) in period \( t \)

\( q_{wstvt} \) Quantity of waste \( w \) transferred from separation centre \( s \) to plant \( p \) by vehicle type \( v \) in period \( t \)

\( q_{in} \) Quantity of waste \( w \) transferred to separation centre \( s \) in period \( t \)

\( q_{sep} \) Quantity of separated waste \( w \) in separation centre \( s \) in period \( t \)

**Integer variables:**

\( y_{wmsvt}, y_{wstvt}, y_{wsep} \) Number of vehicle type \( v \) used for transportation of waste from municipality \( m \) to separation centre \( s \), from separation centre \( s \) to landfill \( l \), from separation centre \( s \) to plant \( p \) in period \( t \)

**Binary variable:**

\( z_{pt} \) Equals one when plant \( p \) is operating in period \( t \); otherwise zero

### 2.2.2 Objective function

The objective function of the proposed model is shown in (1), where the revenue from the sale of electricity is maximized, from which the total cost of the entire SC network is deducted. The first term in (1) is the revenue gained from selling the electricity in municipalities. The second term is the waste collection cost, followed by the waste separation cost, landfilling cost, and electricity production cost in plants. The sixth term indicates the cost of electricity distribution to municipalities. The last two terms are fixed and variable transportation expenses.

\[
\text{Max } f = \sum_m \sum_{s} I_{mt} \cdot q_{mt} - \left( \sum_m \sum_{s} C_{col}^{mt} \cdot q_{wmst} \right) + \sum_m \sum_{s} C_{sep}^{m} \cdot q_{wmst} + \sum_m \sum_{t} C_{land}^{mt} \cdot q_{lt} + \sum_m \sum_{p} \sum_{s} C_{pro}^{pmt} \cdot q_{pt} + \sum_m \sum_{p} \sum_{s} C_{dis}^{pmt} \cdot q_{pmt} + \sum_m \sum_{p} \sum_{s} \sum_{v} C_{v}^{fix} \cdot (y_{wmsvt} + y_{wstvt} + y_{wsep}) + \sum_s C_{var} \cdot \sum_m \sum_{s} \sum_{v} (D_{ms} \cdot y_{wmsvt} + D_{st} \cdot y_{wstvt}) + D_{sp} \cdot y_{wsep})
\]  

(1)

### 2.2.3 Constraints

#### i. Waste collection points

A municipality is composed of different waste collection points, where households can place their produced waste, as shown in (2). Normally, private waste companies, also known as separation centres, arrange the waste transportation, since most municipalities do not have waste collection vehicles of their own. Hence, the MSW is collected on a weekly basis using garbage trucks, as shown in (3).

\[
\sum_{c} A_{wct} = q_{wmnt} \quad \forall w \in W, m \in M, t \in T
\]  

(2)

\[
q_{wmnt} = \sum_{s} q_{wmsvt} \quad \forall w \in W, m \in M, t \in T
\]  

(3)

#### ii. Waste handling in separation centres

Total waste inlet to a separation centre is the sum of the distributed waste from different municipalities, as given in (4). Separation centres are obliged to organize the collected waste and prepare them for further utilization, either recovery or disposal of waste. Equation (5) indicates the amount of separated waste, which can be used for energy recovery in WtE plants. Equation (6) shows that the unusable portion of the waste ends up in landfills. Equation (7) ensures that the potential waste that can be transferred to the WtE plants will not surpass the total amount of separated waste.

\[
q_{in} = \sum_{m} \sum_{s} q_{wmsvt} \quad \forall w \in W, s \in S, t \in T
\]  

(4)

\[
q_{sep} = \alpha_{wst} \cdot q_{in} \quad \forall w \in W, s \in S, t \in T
\]  

(5)

\[
\sum_{s} q_{wstvt} - q_{sep} \geq q_{wst} \quad \forall w \in W, s \in S, t \in T
\]  

(6)

\[
\sum_{p} \sum_{v} q_{wsep} \leq q_{sep} \quad \forall w \in W, s \in S, t \in T
\]  

(7)
iii. Waste transportation flow
Equations (8) to (10) calculate the number of vehicles used for the transfer of waste from municipalities to separation centres, and from separation centres to landfills and WtE plants. The CO₂ emission is the main greenhouse gas emission from transportation, which is directly related to the amount and type of fuel consumed. It is assumed that fuel consumption is only based on the distance travelled and the load does not raise the fuel consumption. Equation (11) ensures that the amount of CO₂ emission does not exceed the permissible emission limit.

\[
\sum_{w} \frac{q_{wmsvt}}{V_{C_v}} \leq y_{msvt} \quad \forall m \in M, s \in S, v \in V, t \in T \tag{8}
\]

\[
\sum_{w} \frac{q_{wslvt}}{V_{C_v}} \leq y_{slvt} \quad \forall s \in S, l \in L, v \in V, t \in T \tag{9}
\]

\[
\sum_{w} \frac{q_{wspt}}{V_{C_v}} \leq y_{spvt} \quad \forall s \in S, p \in P, v \in V, t \in T \tag{10}
\]

\[
\sum_{v} F_{v} \cdot E_{CO_2} = \left( \sum_{m} D_{ms} \cdot y_{msvt} + \sum_{l} D_{sl} \cdot y_{slvt} + \sum_{p} D_{sp} \cdot y_{spvt} \right) \leq AE_{CO_2} \quad \forall s \in S, t \in T \tag{11}
\]

iv. Waste disposal in landfills
A landfill receives any useless MSW from different separation centres as shown in (12). Municipal waste landfills receiving a mixture of MSW have limited disposal capacity, where the waste received from all waste separation centres during period \( t \) should not exceed its capacity as shown in (13). Decomposition of solid waste in landfills generates a considerable amount of the CH₄ emission. Equation (14) shows the permitted CH₄ emitted from landfills, which is according to the emission standards. It is assumed that CH₄ generation depends only on the amount of MSW landfilled, and it does not increase with time, i.e. one-time emission from the point of entry until the end of the biological decomposition process.

\[
q_{lt} = \sum_{s} \sum_{v} \sum_{w} q_{wslvt} \quad \forall l \in L, t \in T \tag{12}
\]

\[
q_{lt} \leq LC_{lt} \quad \forall l \in L, t \in T \tag{13}
\]

\[
E_{CH_4} \cdot q_{lt} \leq AE_{CH_4} \quad \forall l \in L, t \in T \tag{14}
\]

v. Waste processing in WtE plants
A WtE plant facilitated with a specific technology receives source-sorted MSW as fuel from different separation centres, as given in (15). Each plant has a fixed capacity for treating the waste to generate electricity as shown in (16). Equation (17) calculates the amount of electricity that can be produced in WtE plants. Each facility has a capacity limit for producing electricity; hence, the amount of generated electricity is restricted to the maximum capacity level of the plant as given in (18).

\[
q_{wpt} = \sum_{s} \sum_{v} q_{wspt} \quad \forall w \in W, p \in P, t \in T \tag{15}
\]

\[
P_{C_{wpt}} \cdot z_{pt} \leq q_{wpt} \leq P_{C_{wpt}} \cdot z_{pt} \quad \forall w \in W, p \in P, t \in T \tag{16}
\]

\[
q_{pt}^{el} = \sum_{w} q_{wpt} \cdot Y_{wpt} \cdot \varphi_{p} \quad \forall p \in P, t \in T \tag{17}
\]

\[
q_{pt}^{el} \leq PC_{pt}^{el} \quad \forall p \in P, t \in T \tag{18}
\]

The permitted level of CO₂ emission from WtE plants according to existing emission standards is given in (19). Equation (20) shows the total electricity transferred from a WtE plant to municipalities considering the electricity losses at distribution grids.

\[
\sum_{m} e_{wp} \cdot q_{wpt} \leq AE_{CO_2} \quad \forall p \in P, t \in T \tag{19}
\]

\[
\sum_{m} q_{pm}^{el} = q_{pt}^{el} \cdot (1 - \chi_{p}) \quad \forall p \in P, t \in T \tag{20}
\]

vi. Electricity consumers
The total quantity of electricity in a municipality is equal to the total amount of electricity transferred from all WtE plants, as indicated in (21). Equation (22) shows that the total electricity transfer should be equal to or less than the electricity demand, and (23) indicates the lost electricity demand. It should be noted that lost sale of electricity is not penalized since there are plenty of electricity suppliers.

\[
q_{mt}^{el} = \sum_{p} q_{pm}^{el} \quad \forall m \in M, t \in T \tag{21}
\]

\[
q_{mt}^{el} \leq D_{mt}^{el} \tag{22}
\]

\[
l_{mt}^{el} = D_{mt}^{el} - q_{mt}^{el} \quad \forall m \in M, t \in T \tag{23}
\]

3. A NUMERICAL EXAMPLE
In this section, a numerical example is provided in order to show how the proposed model is able to identify the optimal processing route for the best utilization and management of MSW in WtE plants. The considered multi-level SC problem consists of 5 cities, where each city owns 10 collection centres, 5 separation centres, 3 WtE plants, 1 landfill, 5 consumer locations, and 3 types of waste collection trucks with 10, 12.5, and 14 tons of loading capacity, respectively. The CO₂ emission from transport by vehicles is 2.64 kg CO₂ per litre of diesel fuel. It is assumed that the fuel consumption for trucks 1, 2, and 3 is 0.300, 0.313, and 0.357 litre per kilometre, respectively. The considered waste is non-reusable, non-recyclable, and non-biodegradable MSW with a low moisture content that is suitable for combustion. Related data is taken from Santibañez-Aguilar et al. (2015). The waste processing technologies used for electricity generation are incineration with the capacity of processing 1000 tons of MSW per day and energy potential of 600 kWh per ton of waste, gasification having capacity of 900 tons MSW/day and 700 kWh/ton waste, and pyrolysis with 700 tons MSW/day and 650 kWh/ton waste. It is assumed that overall energy efficiency for all three technologies is 90 %, and the separation factor is 90 %. Moreover, seasonal aspects of MSW generation and electricity demand are embedded into the model data, where both waste generation and electricity demand are higher during winter and summer. The planning horizon is one year and the length of the time period used in the computational experiments is one week to satisfy weekly fluctuating demands imposed by the cities. Table 1 shows the total production of waste and electricity demand in the five considered cities.
Table 1. Waste generation and electricity demand in each city

<table>
<thead>
<tr>
<th>City</th>
<th>Waste (kton/year)</th>
<th>Electricity demand (GWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>305.98</td>
<td>113.17</td>
</tr>
<tr>
<td>2</td>
<td>140.99</td>
<td>52.15</td>
</tr>
<tr>
<td>3</td>
<td>38.40</td>
<td>14.20</td>
</tr>
<tr>
<td>4</td>
<td>68.30</td>
<td>25.26</td>
</tr>
<tr>
<td>5</td>
<td>367.98</td>
<td>129.14</td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSIONS

The presented MILP model is coded in GAMS and solved by employing CPLEX solver. The model is composed of 18261 constraints, 9837 continuous variables, 7020 integer variables, and 156 binary variables, and solved in 31.36 seconds. With electricity price of 0.21 USD/kWh, the resulting annual profit is 7.24 MUSD. The total annual revenue obtained from selling the electricity is 70.12 MUSD. The total cost of the SC network is 62.88 MUSD/year, which comprises the collection cost (36.64 %), waste transportation cost (28.94 %), separation cost (21.98 %), electricity production cost (7.02 %), electricity transfer cost (4.68 %), and landfilling cost (0.74 %). Based on the considered input data, electricity demand is fulfilled during each period, and no loss incurred due to lost sales, where incineration, gasification, and pyrolysis plants contributed to the generation of 193.96, 38.47, and 101.49 GWh electricity during a year, respectively. Evidently, incineration led to a more profitable conversion technology, which can be due to having a higher capacity for processing the waste and a lower operating cost.

These results are obtained based on the conversion factors of 2.16 MJ energy/kg waste in incineration plant, 2.52 MJ energy/kg waste in gasification plant, and 2.34 MJ energy/kg waste in pyrolysis plant. To explore the impact of conversion rate on electricity generation and total system profit, various conversion rates are examined, and the results are presented in Fig. 2.

![Fig. 2. Impact of conversion rate changes on profit and electricity generation.](image)

From Fig. 2, it can be observed that total SC profit reduces with the decrease in conversion rate. The profit drops significantly with the reduction in the conversion rate from 0 to 20 % (by 39 %), and a 40 % decrease will result in a negative profit (- 5.62 MUSD). Though reducing the conversion rate does not affect the collection, separation, and landfilling costs, and even lowers the electricity transfer cost, it increases the total production and transportation costs. The reason for the increase in production cost can be due to the increase in the number of production frequencies, since the model tries to meet the electricity demand, and production occurs more frequently. With the initial conversion rate, production frequency in gasification plant is 24 times in one year, where with the 20 % and 30 % decrease in conversion rates, production frequency increases to 40 and 52 times, respectively. Besides, transportation cost rises because of the increase in the number of waste transfers to plants, as the decrease in waste conversion rate necessitates the increase in production to reduce the lost demand. Twenty percent and 30 % decrease in conversion rates will increase the number of waste transfers from separation centres to plants from 51522 during a year to 62787 and 66995, respectively. Thirty percent decrease in conversion rates resulted in an increase in production cost by 0.18 MUSD and transportation cost by 1.95 MUSD. Moreover, the profit drops due to the increase in lost sale. Reducing the conversion rate by 20 % and 30 % causes the unfulfillment of electricity demand by 5.96 GWh/year and 22.81 GWh/year, respectively. The results also show that the lowest amount of CO₂ emission by WtE operations is obtained by the initial conversion rate, and it increases when the conversion rate for all plants decreases, where a 50 % drop in conversion rates increases the CO₂ emission by 21 %.

Energy efficiency of a WtE technology is affected by various technical and non-technical factors such as pre-treatment process, the content of waste, and the amount of MSW to be treated. Therefore, different energy efficiency percentages are examined in order to assess their impacts on electricity generation. The results are depicted in Fig. 3. From Fig. 3, it can be observed that by considering higher energy efficiency, mostly the electricity demand is satisfied by the incineration plant, and less production is done in the gasification plant. However, by the decrease in energy efficiency percentage, as the model tries to meet the demand and reduce the lost sale, production quantity increases in gasification plant. Obviously, the less energy efficient, the less profitable is the system, where the reduction in energy efficiency from 90 % to 70 % will drop the total SC profit by 49 %, and energy efficiency of 60 % will generate a total profit of - 1.32 MUSD.

![Fig. 3. Impact of energy efficiency on electricity generation.](image)

Next, various MSW separation rates are examined in order to investigate its environmental footprint, as well as its impact on the SC network performance. Based on the capacity and environmental restrictions imposed by separation centres and landfills, the separation rate can be up to 90 %, which causes the full satisfaction of electricity demand by WtE plants. When the separation rate decreases, WtE plants will not be able to fully meet the electricity demand, which brings about the drop...
in total net profit of the system, as shown in Fig. 4. The results show that the decrease in waste separation rate increases the landfilling and transportation costs, and finally results in increasing the total cost. It can be observed that the profit remarkably falls with the decrease in the separation rate from 90 % to 70 % (by 81 %), which is due to the increase in transportation cost by 4.72, landfilling cost by 0.92, and production cost by 0.06 MUSD. Reducing the separation rate to 60 % results in a profit of – 4.60 MUSD, mainly due to the rise in transportation cost and lost sale, where 17.72 GWh/year of total electricity demand is not met. Moreover, decreasing the separation rate increases the pollution caused by waste disposal in landfills.

Fig. 4. Effect of MSW separation rate on system performance.

Finding the optimum levels for waste transfers during each period among all the entities of the SC network resulted in determining the optimal number of vehicles required for waste delivery, and thus obtaining the lowest transportation cost. Accordingly, by separation rate of 90 %, during a year 99803 trips using truck type 1, 49407 trips by truck type 2, and 55 trips via truck type 3 were carried out within all the entities of SC network. The reason of using truck type 1 more is that it is more environmentally and economically efficient compared to the other truck types. As depicted in Fig. 5, decreasing the separation rate rises the transportation cost due to the increase in the number of trips transferring the waste to landfills, which also increases the CO2 emission from transport. Change of separation rate from 90 % to 70 % increases the total number of trips during a year from 149265 to 159584 trips.

Fig. 5. Impact of separation rate changes on CO2 emission and transportation cost.

It is important to note that considering each waste source (city) individually reduces the profit remarkably, since there is not enough waste available in all cities to meet the demand. Moreover, the costs associated with production and transportation increase significantly. Considering cities collectively results in reducing the excessive inventory or stock-outs as additional required waste materials in plants can be supplied from different waste supply sources. More information on the effect of the integration of waste sources on demand satisfaction and the system performance can be found in Mohammadi et al. (2019).

5. CONCLUSIONS

The proposed integrated SC is concerned with planning, coordinating, and controlling functions involved in sustainable WtE. An MILP is presented for the optimal planning of an MSW management problem with multiple waste collection centres, separation centres, WtE plants, landfills, and consumer locations. The model aims to identify the optimal processing route for the best utilization and conversion of MSW into electricity, in addition to maximizing the net profit of the system. The presented model can determine the quantity of waste supplied from cities to separation centres and from separation centres to processing plants, the amount of waste in plants transferred to WtE technologies, and the quantity of generated electricity transferred from plants to the cities. It is shown that increasing the waste separation rate results in decreasing the emission caused by waste disposal, reducing the lost demand, and increasing the profit. Moreover, considering higher energy efficiency and WtE conversion factor reduces the amount of waste ending up to landfills, and thus improves the system performance, both in terms of profitability and environmental impacts. Further research should be carried out to investigate the consequences of waste processing only in controlled landfill sites and compare the results with the waste treatment in WtE plants.

REFERENCES


