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Sustainable supply chain network design for the optimal utilization of municipal solid waste

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Abstract

The growing waste generation, increasing environmental regulations, and limited land area for waste disposal necessitate an effective and efficient waste supply chain management solution in terms of both socioeconomic perspectives and environmental sustainability. Waste management is connected to supply chain decisions as it involves waste generation, collection, separation, transportation, processing, and disposal. Accordingly, this paper develops a mixed integer linear programming model for the optimal planning of a waste management system in a multi-echelon supply chain network, which aims to find a trade-off between supply chain costs, depletion of waste and efficient use of generated waste while considering the environmental impacts. Various recycling and WtE technologies are utilized to convert plastic and mixed waste into value-added products including fuel, electricity, and heat. Though recycling is preferable from an environmental point of view, it is shown that the waste-to-energy option is more economically efficient.

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

Introduction

The amount of municipal solid waste (MSW) is dramatically increasing throughout the world due to the rapid population growth and urbanization, socioeconomic development, and industrialization, in addition to the change in lifestyle and consumption patterns. The MSW management has always been the focus of attention for local authorities and governments because of the growing concerns associated with waste disposal and environmental issues. Disposal of waste is a critical threat to the local and global environment, and if not properly managed, it can cause serious problems. Moreover, improper MSW management harmfully

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affects the social and economic developments, as well as human health due to waste-borne diseases.[1]

Undeniably, the ideal of the entire removal of waste is highly unrealistic. Hence, the best tactic is to control and manage the produced waste in such a way that the process is environmentally efficient, economically affordable, and socially acceptable. MSW is considered as a suitable source for recycling and energy production compared to other waste sources and residue feedstock as it is available throughout the year, it is concentrated (supply locations), and it contributes to revenue generation because of significantly reducing the waste disposal cost.[2]

For successful management of MSW, the waste hierarchy introduced by the waste framework directive of the European Union in 1975 is usually used. It includes various options for managing the physical waste and ranks options from the most to least preferred as: 1) waste avoidance and minimization, 2) reuse, 3) recycling, 4) energy recovery and 5) disposal. However, environmental experts have come to the conclusion that the goals set for the waste depletion rate may never be attained without energy recovery.[3] Waste-to-Energy (WtE) has become a viable option for many countries as an effective waste management (WM) solution in a sustainable way and as the preeminent method of waste disposal.[4]

The WM can be considered as a strategic supply chain (SC) problem as it involves the waste generation, collection, separation, distribution, processing, and disposal. It is essential to consider the whole SC when a WM system is taken into account, as the efficiency of the WM can be enhanced by adopting proper SC management techniques.[5] WM organizations are continuously looking for ways of reducing the cost and improving efficiency by minimizing waste within their internal and external SCs. Moreover, national and international regulations concerning the WM are increasing, and consumers become more concerned about the protection of the environment.[6] All these reasons call for designing and operating an optimal SC network for the effective management of the produced waste.

Consequently, the current study addresses this need by presenting an MSW management problem in a multi-echelon SC network composed of multiple waste collection points, separation centers, recycling and WtE plants, distribution centers (DCs), and consumer locations. The integrated SC optimization problem is formulated as a mixed integer linear programming (MILP) model, which covers various functions such as waste collection at cities, waste separation at separation centers, waste processing at plants, sending the unusable waste to landfills, and selling the end products at the markets. The aim of the proposed model is to identify the optimal processing route for the best utilization and conversion of MSW into recycled and energy products, in addition to maximizing the profit of the entire SC network over a finite planning horizon. To demonstrate the flexibility and practicality of the proposed optimization model, a numerical example is presented.

Waste-to-Energy Features and Techniques

There are three main categories for converting waste materials (also classified as renewable resources) into solid fuels (e.g. coal), liquid fuels (e.g. ethanol, methanol, biodiesel, and Fischer-Tropsch diesel), and gaseous fuels (e.g. Hydrogen (H_2) and methane (CH_4)), namely thermochemical, biochemical, and physicochemical conversion techniques. These fuel sources can then be converted (mainly combusted) to generate heat and electricity or biofuels (transportation fuels), synthetic natural gas and chemicals.

Thermochemical conversion characterized by high temperature and conversion rates is useful for dry waste with a high percentage of non-biodegradable matter and low moisture feedstock.[7] It is used for changing the physical properties and chemical structures of the biomass resources.[8] Potential energy types include heat, steam, electricity, and liquid fuels, as well as biofuels if the feedstock is biomass. The three principal methods of thermochemical conversion technologies include conventional incineration, pyrolysis and gasification. Other thermochemical processes are plasma gasification, hydrothermal carbonization, thermal depolymerization, direct liquefaction and torrefaction. Direct combustion (conventional incineration) is the most common technology for producing heat and electricity from waste. Combined heat and power (CHP), also known as cogeneration systems, can significantly increase a plant's operational efficiency, more than the facilities only generating electricity, and decrease the energy costs.[9] According to the World Bank, incineration helps reducing the volume of disposed waste by up to 90 % and weights up to 75 %.

The amount and types of generated products depend on the employed thermochemical technologies. For instance, fast pyrolysis (heating organic materials to 400-650°C in absence of oxygen (O_2)) yields organic vapors, which are then condensed to pyrolysis oil, syngas (that can be burned to produce energy), and charcoal (sold as a valuable product). A slow pyrolysis (temperature 300-500°C) produces organic gas (used as power production) and charcoal.[1] Regarding the electricity and heat generation, in general, conventional WtE plants that use mass-burn incineration (temperature above 1000°C) can convert one ton of MSW to about 500-600 kWh for use by the local utility, and to 1000 kWh for district heating. Conventional gasification (temperature about 750°C) generates around 600-700 kWh of electricity per ton of MSW, and the potential electricity generation using pyrolysis technology is about 580-650 kWh/ton of MSW.

The benefits of WtE compared to landfilling include reducing the cost of waste transportation to landfills often located far away from municipalities and decreasing the landfilling cost, as well as reducing the burden on the land required for waste disposal because of limited landfill space. Due to the ever-increasing energy demand, the world's energy markets today greatly rely on finite non-renewable energy sources such as fossil fuels, coal, petroleum crude oil and natural gas.[10] The use of waste for production of renewable energy and fuels reduces the world's dependency on traditional fossil fuels and contributes to the conservation of natural resources, in addition to decreasing the carbon dioxide (CO_2) emissions generated from coal, oil, and natural gas power plants. More importantly, the traditional solid waste burning in large furnaces with little or no concerns or regulations for air pollution and ash disposal no longer exist. Currently, WtE plants produce less greenhouse gas (GHG) such as CH_4 compared to the landfills.[11] In terms of material recovery, the ferrous and non-ferrous metals can be recovered from the bottom ash resulting from incineration process.[12]

Waste Supply Chain Management

According to Cooper et al.[13], the sustainable superior performance as the long-term strategy of a manufacturing corporation highly depends on its ability to become an entirely integrated partner within the SC context. Such SC strategy focuses on the integration of internal and external processes of the organization across the chain to better serve the customers while improving the performance of each member of the SC network.[14]

Some of the advantages of integrating the SC network into the WM system are the smooth flow of waste among the SC entities[15], balancing the vehicle loads and minimizing the transportation cost[16], balancing the inventory levels and reducing the inventory cost[17], and improving responsiveness and increasing the service level[18]. Besides, it contributes to extracting the maximum value from the generated waste[19], increasing the use of renewable source of energy[20], acquiring a better energy efficiency[21], lowering the environmental impacts[22], and accelerating the transition towards a circular economy[23].

The research to date has tended to focus on the partial integration of SC functions in WM systems rather than the integrated one and thus, there is a lack of research on this growing area. Despite this, very few studies have investigated the impacts of considering integrated SC networks on WM systems. For instance, an inexact reverse logistics model for MSW management systems was developed by Zhang et al.[24] in order to investigate the interactions between transportation, inventory and production planning in the entire system under uncertainties. Santibañez-Aguilar et al.[25] proposed a mathematical programming model for the optimal planning of the SC associated with the MSW management system to maximize the economic benefit while accounting for technical and environmental issues. In another study, Zhang et al.[26] developed a multi-echelon SC model involving the suppliers, producers, and distributors with the aim of minimizing the system cost and cost-effective allocation of waste to processing facilities and landfills.

Ng et al.[27] proposed a SC network design for efficient utilization of MSW for energy generation using WtE technologies including incineration, gasification and pyrolysis. However, they concluded that the MSW utilization was not economically profitable mainly due to the high cost of WtE technologies. Santibañez-Aguilar et al.[15] presented a multi-objective model considering several functions of the SC for the optimal planning of the reuse of MSW, maximizing the annual profit, and minimizing the social risk. A case study in the region of Mexico was used to investigate the tradeoff between the social, economic, and environmental criteria. Through a study conducted by Diaz-Barriga-Fernandez et al.[28], the strategic and operational planning of an MSW management system was presented with the aim of minimizing the costs associated with transportation, separation, and production of the products obtained from the recycled residues, in addition to increasing the profit of all involved stakeholders.

Collectively, these studies provide important insights into the critical role of a well-designed SC network in enhancing the performance of WM systems. However, previous studies of WM systems have not dealt with the combinations of all essential functions associated with the integrated SC network. The possible explanation for the lack of adequate research on this area could be due to the intricacy in the integration of all components of the SC network. The integrated SC proposed in this study is concerned with planning, coordinating, and controlling functions involved in sustainable WM.

The proposed model focuses on tactical planning level by considering the logistics of existing facilities, use of installed technologies, and the optimal allocation of feedstock and products, as well as the operational decision level by involving the detailed operations of the SC network such as the weekly lot-sizing plan for each plant. By the proposed model, we are able to determine the optimal allocation of the total demand to different DCs, and based on that optimally allocate the waste to existing separation centers and then plants, allocate production of multiple products to different facilities and assign the DCs to plants, in addition to determining the required vehicles for each route. Therefore, the model has been designed to facilitate waste and product transferability across different SC entities. The objective is to minimize the total cost of the entire SC network, and to best fulfill the demand, while not exceeding the supply capacity of separation centers, production capacities in plants, and storage capacities in separation centers, plants and DCs, as well as pre-determined emission limits associated with transportation, plant operations, and landfilling.

Mathematical Model Formulation

In this study, it is assumed that responsibility for managing the MSW belongs to local authorities, in which they organize the collection and disposal of household waste, and carry out the WM tasks themselves. It helps them to gain more direct control over their SCs, and to provide more services, reduce risk, and save time. Multiple product types are produced in different plants by processing via various recycling and WtE technologies. The outputs of recycling plants are recycled items, and WtE plants include intermediate products (e.g. syngas), final products (e.g. fuel), and energy products (heat and electricity). The products are then disseminated to cities through a set of established DCs. It is designated that the consumers located in cities do not order the intermediate products used in the production of final products in WtE plants, and hence they are not transferred to the cities, and their final stop is the DCs. Moreover, it is assumed that the WtE plants through transmission lines and heat pumps directly conduct electricity and heat transfers to consumers in cities, and hence no DC is considered for the heat and electricity. The model proposes the optimum solution to the transportation network system by selecting which vehicle type should travel between the SC entities based on the shortest distance, environmental limits by vehicles and the total number of available vehicles.

Objective Function

i. Revenue:

Equation (1a) expresses the total sales income, which is obtained from the sales of recycled products (N^r) produced by recycling plants (P^r), and final products (N^f) produced by WtE plants (P^e), as well as electricity (N^{el}) and heat (N^h) generated by WtE plants. The intermediate products (N^{int}) produced in WtE plants are only sold at DCs (D^e). It should be noted that due to the considered ownership of waste SC by the local authorities, we have not specifically considered waste buyers and waste suppliers. Therefore, separation centers will not make any profit through selling waste to the plants. Besides, recycling and WtE plants will not make any profit by selling their on-hand waste inventory to the other plants that require more waste in their production processes.

$$R = \sum_{n \in \{N^r \cup N^f \cup N^{el} \cup N^h\}} \sum_{c} \sum_{t} P_{nct} \cdot q_{nct} + \sum_{n \in N^{int}} \sum_{d \in D^e} \sum_{t} P_{ndt} \cdot q_{ndt} \tag{1a}$$

***ii. Collection and separation costs*:**

Equation (1b) shows the total cost incurred for collecting waste from the cities and Eq. (1c) indicates the total cost of separating the collected waste at separation centers.

$$CC = \sum_{w}\sum_{c}\sum_{t} C_{ct}^{col} \cdot W_{wct} \tag{1b}$$

$$SC = \sum_{w}\sum_{s}\sum_{t} C_{wst}^{sep} \cdot q_{wst}^{in} \tag{1c}$$

***iii. Production and inventory costs*:**

Equation (1d) calculates the production cost of all recycled, intermediate, and final products, as well as electricity and heat. Equation (1e) is the inventory cost of waste in separation centers, waste and products in recycling and WtE plants, and products in the DCs.

$$PRC = \sum_{n\in\{N^r\cup N^{int}\cup N^f\cup N^{el}\cup N^h\}}\ \sum_{p\in\{P^r\cup P^e\}}\ \sum_{t} C_{npt}^{prod} \cdot q_{npt} \tag{1d}$$

$$\begin{aligned} IC = {} & \sum_{w}\sum_{s}\sum_{t} C_{wst}^{in} \cdot (i_{wst}^{r} + i_{wst}^{nr}) + \sum_{w}\ \sum_{p\in\{P^r\cup P^e\}}\ \sum_{t} C_{wpt}^{in} \cdot i_{wpt} \\ & + \sum_{n\in\{N^r\cup N^{int}\cup N^f\}}\ \sum_{p\in\{P^r\cup P^e\}}\ \sum_{t} C_{npt}^{in} \cdot i_{npt} + \sum_{n\in\{N^r\cup N^{int}\cup N^f\}}\ \sum_{d\in\{D^r\cup D^e\}}\ \sum_{t} C_{ndt}^{in} \cdot i_{ndt} \end{aligned} \tag{1e}$$

***iv. Shortage cost*:**

Equation (1f) shows the back-ordering cost incurred by recycling and WtE plants, when they are unable to fulfill orders of products at the due date and must complete the orders in the next period. It is assumed that if a WtE plant cannot fully satisfy the orders of intermediate products, electricity and heat at the due date, a shortage will occur, and the portion of unmet demand is lost. Lost sale cannot be fulfilled in the next period, and it results in a shortage cost.

$$\begin{aligned} SHC = {} & \sum_{n\in\{n^r\cup n^f\}}\ \sum_{p\in\{P^r\cup P^e\}}\ \sum_{d\in\{D^r\cup D^e\}}\ \sum_{t} C_{npdt}^{back} \cdot b_{npdt} + \sum_{n\in n^{int}}\ \sum_{p\in P^e}\ \sum_{d\in D^e}\ \sum_{t} C_{npdt}^{lost} \cdot l_{npdt} \\ & + \sum_{n\in\{n^{el}\cup n^h\}}\ \sum_{p\in P^e}\ \sum_{c}\ \sum_{t} C_{npct}^{lost} \cdot l_{npct} \end{aligned} \tag{1f}$$

***v. Transportation cost*:**

Equation (1g) expresses the transportation costs between the collection centers and separation centers, from separation centers to landfills and plants, between plants, from plants to DCs, and from DCs to the cities. Since separation centers own their fleet of garbage trucks, they are responsible for carrying the waste. Moreover, plants have their own truck fleets to conduct and control their own product delivery. Therefore, due to the considered ownership structure, our model is insensitive to the effect of the shipment quantity. The transportation system has been analyzed according to its specific parameters including time and distance-dependent costs, the number of trips, fuel consumption, vehicle's speed and capacity, and their environmental impact. Variable cost varies with the transportation amount and is proportional to the distance and time of traveling such as fuel and driver costs. The distance-based costs are calculated according to the distance of a trip (km), fuel consumption of the vehicle (l/km), and the price of fuel (USD/l). Fixed cost remains constant within a period and is not dependent on the transportation load such as insurance cost and taxes. The heat and electricity transfer cost is simply calculated by the amount of energy transferred (MWh) and the per unit transfer cost.

$$\begin{aligned}TC =& \textstyle\sum_c \sum_s \sum_v \sum_t (C_v^{dis} \cdot D_{cs}^{CS} \cdot y_{csvt} + C_v^{time} \cdot \frac{D_{cs}^{CS}}{T_v} \cdot y_{csvt} + C_v^{fix} \cdot y_{csvt}) \\ &+ \textstyle\sum_s \sum_l \sum_v \sum_t (C_v^{dis} \cdot D_{sl}^{SL} \cdot y_{slvt} + C_v^{time} \cdot \frac{D_{sl}^{SL}}{T_v} \cdot y_{slvt} + C_v^{fix} \cdot y_{slvt}) \\ &+ \textstyle\sum_s \sum_{p\in\{P^r \cup P^e\}} \sum_v \sum_t (C_v^{dis} \cdot D_{sp}^{SP} \cdot y_{spvt} + C_v^{time} \cdot \frac{D_{sp}^{SP}}{T_v} \cdot y_{spvt} + C_v^{fix} \cdot y_{spvt}) \\ &+ \textstyle\sum_{p\in\{P^r \cup P^e\}} \sum_l \sum_v \sum_t (C_v^{dis} \cdot D_{pl}^{PL} \cdot y_{plvt} + C_v^{time} \cdot \frac{D_{pl}^{PL}}{T_v} \cdot y_{plvt} + C_v^{fix} \cdot y_{plvt}) \\ &+ \textstyle\sum_{p\in\{P^r \cup P^e\}} \sum_{\tilde{p}\in\{P^r \cup P^e\}} \sum_v \sum_t (C_v^{dis} \cdot D_{p\tilde{p}}^{PP} \cdot y_{p\tilde{p}vt} + C_v^{time} \cdot \frac{D_{p\tilde{p}}^{PP}}{T_v} \cdot y_{p\tilde{p}vt} + C_v^{fix} \cdot y_{p\tilde{p}vt}) \\ &+ \textstyle\sum_{p\in\{P^r \cup P^e\}} \sum_{d\in\{D^r \cup D^e\}} \sum_v \sum_t (C_v^{dis} \cdot D_{pd}^{PD} \cdot y_{pdvt} + C_v^{time} \cdot \frac{D_{pd}^{PD}}{T_v} \cdot y_{pdvt} + C_v^{fix} \cdot y_{pdvt}) \\ &+ \textstyle\sum_{d\in\{D^r \cup D^e\}} \sum_c \sum_v \sum_t (C_v^{dis} \cdot D_{dc}^{DC} \cdot y_{dcvt} + C_v^{time} \cdot \frac{D_{dc}^{DC}}{T_v} \cdot y_{dcvt} + C_v^{fix} \cdot y_{dcvt}) \\ &+ \textstyle\sum_{n\in\{n^{el} \cup n^h\}} \sum_{p\in P^e} \sum_c \sum_t C_{npct}^{dist} \cdot q_{npct}\end{aligned} \tag{1g}$$

***vi. Emission and waste production penalty costs*:**

Equation (1h) computes the penalty cost that separation centers, plants, landfills, and DCs should pay if their waste, CO_2, and CH_4 generation exceed the pre-determined waste production and emission limits.

$$\begin{aligned}EC =& \sum_s \sum_t C_{st}^{e} \cdot e_{st}^{exc} + \sum_{p\in\{P^r \cup P^e\}} \sum_t C_{pt}^{e} \cdot e_{pt}^{exc} + \sum_{p\in\{P^r \cup P^e\}} \sum_t C_{pt}^{w} \cdot w_{pt}^{exc} + \sum_{d\in\{D^r \cup D^e\}} \sum_t C_{dt}^{e} \cdot e_{dt}^{exc} \\ &+ \sum_{p\in\{P^r \cup P^e\}} \sum_t C_{pt}^{oper} \cdot e_{pt}^{oper} + \sum_l \sum_t C_{lt}^{e} \cdot e_{lt}^{exc}\end{aligned} \tag{1h}$$

***vii. Disposal cost*:**

Equation (1i) indicates the disposal cost charged for each ton of solid waste delivered to landfills.

$$LC = \sum_s \sum_l \sum_v \sum_t C_{lt}^{land} \cdot q_{slvt} + \sum_{p\in\{P^r \cup P^e\}} \sum_l \sum_v \sum_t C_{lt}^{land} \cdot q_{plvt} \tag{1i}$$

Finally, the objective function of the proposed problem is shown in Eq. (1), where the revenue from sales is maximized from which the total cost of the entire SC network is deducted.

$$Max\ f = R - (CC + SC + PRC + IC + SHC + TC + EC + LC) \tag{1}$$

Constraints

***i. Waste collection center*:**

The cities considered as collection centers produce different types of MSW. Therefore, various vehicle types periodically distribute all the produced waste from cities to different separation centers as given in Eq. (2). Several vehicle types such as truck, van, and trailer, consuming different types of fuel such as gasoline, diesel, petrol, and gas, can carry out the shipment. For simplicity, it is assumed that all waste types are collected together and transferred with the same vehicle type. Equation (3) calculates the number of each vehicle type from collection centers to separation centers.

$$W_{wct} = \sum_{s}\sum_{v} q_{wcsvt} \quad \forall w \in W, c \in C, t \in T \tag{2}$$

$$y_{csvt} - 1 \leq \frac{\sum_{w} q_{wcsvt}}{L_v} \leq y_{csvt} \quad \forall c \in C, s \in S, v \in V, t \in T \tag{3}$$

***ii. Waste separation center*:**

Equation (4) shows the total amount of each waste type entering the separation center during each period. Equation (5) represents the amount of separated waste, which is equal to the separation factor multiplied by the total waste received in the separation center during each period. Then, the unusable portion is transferred to the landfills, and the remaining waste is further sorted out. In this paper, the usable waste is divided into two categories of recyclable waste processed in recycling plants and non-recyclable waste treated in WtE plants as presented in Eqs. (6) and (7). Some waste such as plastics can be used in both recycling and energy recovery processes. In practice, the waste is initially sorted for recycling, because recycling is extensively preferred over energy recovery. However, due to the chemical structure of some types of waste (e.g. polyvinyl chloride (PVC) plastic waste), not all the waste types are recyclable or even reusable.

$$q_{wst}^{in} = \sum_{c}\sum_{v} q_{wcsvt} \quad \forall w \in W, s \in S, t \in T \tag{4}$$

$$q_{wst}^{sep} = \alpha_{wst}^{sep} \cdot q_{wst}^{in} \quad \forall w \in W, s \in S, t \in T \tag{5}$$

$$q_{wst}^{r} = \alpha_{wst}^{r} \cdot q_{wst}^{sep} \quad \forall w \in W, s \in S, t \in T \tag{6}$$

$$q_{wst}^{nr} = q_{wst}^{sep} - q_{wst}^{r} \quad \forall w \in W, s \in S, t \in T \tag{7}$$

Equation (8) computes the amount of waste that is transported to the landfills, which is the remaining waste from the total received waste from which the useful waste is separated. MSW is possible to degrade with time, which results in decreasing stock level by ρ % each period. Thus, in every period the deteriorated portion of stored waste kept from the previous period is transferred to the landfills as well. Equation (9) ensures that the potential waste that can be transferred to the recycling and WtE plants will not surpass the total amount of separated waste received in each period plus the usable stored waste available from previous periods. It is obvious that only recyclable waste $(q^{r}_{wst} + (1 - \rho^{r}_{wst}) \cdot i^{r}_{ws(t-1)})$ can be transferred to recycling plants and non-recyclable waste $(q^{nr}_{wst} + (1 - \rho^{nr}_{wst}) \cdot i^{nr}_{ws(t-1)})$ to WtE plants. Initial inventory levels of the recyclable and non-recyclable waste in a separation center are considered to be equal to U^{r}_{ws} and U^{nr}_{ws}, respectively, which they are equal to or greater than zero. For each separation center, the inventory level of each type of waste during each period equals the amount of waste from the previous period, plus the separated waste, subtracted by the total amount of waste transported to plants and landfills, as shown in Eqs. (10) and (11). The inventory level of the waste cannot exceed the separation center's storage capacity, where $i^{r}_{wst} \leq S^{r}_{ws}$ and $i^{nr}_{wst} \leq S^{nr}_{ws}$. Equations (12) and (13) calculate the number of vehicles used for the transportation of waste from separation centers to landfills, and recycling and WtE plants, respectively.

$$\sum_{l}\sum_{v} q_{slvt} \leq \sum_{w}\left(q^{in}_{wst} - q^{sep}_{wst} + \rho^{r}_{wst} \cdot i^{r}_{ws(t-1)} + \rho^{nr}_{wst} \cdot i^{nr}_{ws(t-1)}\right) \quad \forall s \in S, t \in T \tag{8}$$

$$\sum_{p \in \{P^{r} \cup P^{e}\}} \sum_{v} q_{wspvt} \leq q^{r}_{wst} + q^{nr}_{wst} + (1 - \rho^{r}_{wst}) \cdot i^{r}_{ws(t-1)} + (1 - \rho^{nr}_{wst}) \cdot i^{nr}_{ws(t-1)} \quad \forall w \in W, s \in S, t \in T \tag{9}$$

$$i^{r}_{wst} = i^{r}_{ws(t-1)} + q^{r}_{wst} - \sum_{p \in P^{r}} \sum_{v} q_{wspvt} - \rho^{r}_{wst} \cdot i^{r}_{ws(t-1)} \quad \forall w \in W, s \in S, t \in T \tag{10}$$

$$i^{nr}_{wst} = i^{nr}_{ws(t-1)} + q^{nr}_{wst} - \sum_{p \in P^{e}} \sum_{v} q_{wspvt} - \rho^{nr}_{wst} \cdot i^{nr}_{ws(t-1)} \quad \forall w \in W, s \in S, t \in T \tag{11}$$

$$y_{slvt} - 1 \leq \frac{q_{slvt}}{L_{v}} \leq y_{slvt} \quad \forall s \in S, l \in L, v \in V, t \in T \tag{12}$$

$$y_{spvt} - 1 \leq \frac{\sum_{w} q_{wspvt}}{L_{v}} \leq y_{spvt} \quad \forall s \in S, p \in \{P^{r} \cup P^{e}\}, v \in V, t \in T \tag{13}$$

In transportation, the principal GHG is CO_2, which is directly related to the amount and type of fuel consumed. As the use of fuel gives rise to emissions, emission limits based on the environmental regulations attached to the transport are taken into account. Equation (14) calculates the amount of emission exceeding the emission limit (AE^{tran}_{st}), which incurs a penalty cost paid by the separation center. Since it is difficult to predict how much a given load costs in fuel consumed, it is assumed that fuel consumption is only based on the distance traveled and the load does not raise the fuel consumption.

$$e_{st}^{exc} = max\left\{0, \left(\sum_{c}\sum_{v} D_{cs}^{CS}\cdot y_{csvt}\cdot F_v \cdot E_v^{CO_2} + \sum_{l}\sum_{v} D_{sl}^{SL}\cdot y_{slvt}\cdot F_v\cdot E_v^{CO_2} + \sum_{p\in\{P^r\cup P^e\}}\sum_{v} D_{sp}^{SP}\cdot y_{spvt}\cdot F_v\cdot E_v^{CO_2}\right) - AE_{st}^{tran}\right\} \quad \forall s\in S, t\in T \tag{14}$$

Since MILP models cannot handle max-functions (non-continuous, non-linear), Eq. (14) is reformulated as Eq. (14a). This reformulation is applied to all the equations presented in this paper, in which where a max function is required to select the maximum amount between zero and a term, it is converted to equal to or greater than that term. It is assumed that left-hand side of this type of equation must be equal to or greater than zero.

$$e_{st}^{exc} \geq \left(\sum_{c}\sum_{v} D_{cs}^{CS}\cdot y_{csvt}\cdot F_v \cdot E_v^{CO_2} + \sum_{l}\sum_{v} D_{sl}^{SL}\cdot y_{slvt}\cdot F_v\cdot E_v^{CO_2} + \sum_{p\in\{P^r\cup P^e\}}\sum_{v} D_{sp}^{SP}\cdot y_{spvt}\cdot F_v\cdot E_v^{CO_2}\right) - AE_{st}^{tran} \quad \forall s\in S, t\in T \tag{14a}$$

iii. Waste processing plants

It is considered that recycled products are produced from recyclable waste in recycling plants through a single process. In WtE plants, before producing the final product (e.g. fuel, electricity, heat), the intermediate products (e.g. pyrolysis oil, syngas, heat) can be formed during a middle step of a conversion process, which might require further processing before it is saleable to the end users. This further processing might be done by the same plant or by another producer. The valuable intermediate products can be sold to other producers to increase the profitability of the system. In this paper, the plants who purchase the intermediate products are not taken into account.

Equation (15) shows the amount of waste that a plant requests from the separation centers per period, which equals to the amount of products a plant should produce in each period (given in Eqs. (16) and (17)) multiplied by the amount of waste required to produce a unit of a product, minus the available waste stock. Therefore, Eq. (15) is only for ordering the waste required in the production of recyclable and intermediate products ($n \in \{N^r, N^{int}\}$). For the intermediate products, the production quantity is equal to demand of intermediate products requested by a DC, plus the amount of intermediate products used in the production of final products, heat, and electricity, minus the on-hand inventory of intermediate product, as given in Eq. (16).

The production quantity of recycled and final products is equal to total demand of product requested by different DCs plus back-order amount of unmet product demand from the previous period that a plant owes to different DCs, minus the available stock, as shown in Eq.

(17). It is also presumed that the corresponding WtE plants carry out the distribution of heat and electricity, and no DC for the energy products is taken into account. Since heat and electricity are ordered directly from the cities, the production quantity for these product types is simply equal to demand of the product, as presented in Eq. (18). The safety stock coefficient ε_{npt} for producing all product types is considered to reduce opportunity loss due to the stock-outs and to protect the plant against uncertain situations. The safety stock for electricity and heat is to incorporate the heat and electricity losses incurred at electricity grids, the main district heating pipeline, and the district heating distribution network. The value of ε_{npt} should be greater than one.

$$r_{wpt} \geq \sum_{n\{N^r \cup N^{int}\}} (\chi_{wnp} \cdot \tilde{q}_{npt}) - \left((1-\rho_{wpt}) \cdot i_{wp(t-1)}\right) \quad \forall w \in W, p \in \{P^r \cup P^e\}, t \in T \tag{15}$$

production quantity for intermediate products:

$$\tilde{q}_{npt} = \left[(\varepsilon_{npt} \cdot \sum_{d \in D^e} D_{npdt}) + \sum_{n^f} \chi_{nn^f p} \cdot \tilde{q}_{n^f pt} + \chi_{nn^{el} p} \cdot \tilde{q}_{n^{el} pt} + \chi_{nn^h p} \cdot \tilde{q}_{n^h pt}\right] - i_{np(t-1)} \; \forall n \in N^{int}, p \in P^e, t \in T \tag{16}$$

production quantity for recycled products in recycling plants, and final products in WtE plants:

$$\tilde{q}_{npt} = \sum_{d \in \{D^r \cup D^e\}} b_{npd(t-1)} + (\varepsilon_{npt} \cdot \sum_{d \in \{D^r \cup D^e\}} D_{npdt}) - i_{np(t-1)} \quad \forall n \in \{N^r \cup N^f\}, p \in \{P^r \cup P^e\}, t \in T \tag{17}$$

production quantity for energy products in WtE plants:

$$\tilde{q}_{npt} = \varepsilon_{npt} \cdot \sum_{c} D_{npct} \quad \forall n \in \{N^{el} \cup N^h\}, p \in P^e, t \in T \tag{18}$$

Equation (19) shows that the total amount of waste entering each plant from all separation centers during each period is equal to or smaller than the required waste in the plant. When demand of waste w in period t is not fully satisfied by all separation centers, the remaining demand can be supplied from other plants subject to the available waste inventory at those plants. Equation (20) indicates the potential amount of waste a plant requires to order from other production plants in each period. Here p is the receiving plant and $\tilde{p}$ is the giving plant. If separation centers and plants cannot meet the requested amount, the portion of unmet demand of waste is assumed to be lost and no penalty cost for lost units of waste demand occurs by the separation centers or the plants. Equation (21) presents the total amount of waste entering a plant in each period.

$$\sum_{s} \sum_{v} q_{wspvt} \leq r_{wpt} \quad \forall w \in W, p \in \{P^r \cup P^e\}, t \in T \tag{19}$$

$$\sum_{\tilde{p}\in\{P^r\cup P^e\}}\sum_{v} r_{w\tilde{p}pvt} \geq r_{wpt} - \sum_{s}\sum_{v} q_{wspvt} \quad \forall w \in W, p \in \{P^r \cup P^e\} \,\&\, p \neq \tilde{p}, t \in T \tag{20}$$

$$q_{wpt} = \sum_{s}\sum_{v} q_{wspvt} + \sum_{\tilde{p}\in\{p^r\cup p^e\}}\sum_{v} r_{w\tilde{p}pvt} \quad \forall w, p \in \{P^r \cup P^e\} \,\&\, p \neq \tilde{p}, t \in T \tag{21}$$

Equation (22) limits the amount of waste to be transferred from plant p to waste processing technologies type j ($j \in \{J^r, J^{int}\}$) and other plants ($\tilde{p}$) in period *t*, which should not exceed the usable on-hand inventory plus total amount of waste received by plant p in the current period. It is obvious that a plant first uses the waste required in its production process, and when there is the adequate waste to be sent to other plants, the plant ships the waste considering its inventory level. It is assumed that if during period *t* there is a transfer into plant p by other plants, there cannot be any transfer out from plant p to other plants ($\tilde{p}$) during that period.

$$\sum_{j\in\{j^r\cup j^{int}\}} q_{wpjt} + \sum_{\tilde{p}\in\{p^r\cup p^e\}}\sum_{v} r_{wp\tilde{p}vt} \leq \left(1-\rho_{wpt}\right)\cdot i_{wp(t-1)} + q_{wpt} \quad \forall w \in W, p \in \{P^r \cup P^e\} \,\&\, p \neq \tilde{p}, t \in T \tag{22}$$

The initial inventory level of waste in a plant is considered to be equal to U_{wp}. Equation (23) represents the balance for the inventory of waste at plants at the end of each period, which is the usable waste stored from the previous period, plus the total amount of waste received in the current period, minus waste transferred to processing technologies and other plants. The upper limit of inventory for each type of waste in a plant is assumed to be S_{wp} (equal to or greater than zero).

$$i_{wpt} = \left(1-\rho_{wpt}\right)\cdot i_{wp(t-1)} + q_{wpt} - \sum_{j\in\{j^r\cup j^{int}\}} q_{wpjt} - \sum_{\tilde{p}\in\{p^r\cup p^e\}}\sum_{v} r_{wp\tilde{p}vt} \quad \forall w \in W, p \in \{P^r \cup P^e\} \,\&\, p \neq \tilde{p}, t \in T \tag{23}$$

Equation (24) defines the capacity limit of each technology used in the conversion of waste to recycled products in recycling plants. Equation (25) shows the amount of yielded product at each recycling plant, which is equal to the total waste distributed to the recycling technologies ($j \in J^r$) multiplied by the conversion rate of β_{wn^rpj}.

$$L^{low}_{wpj}\cdot z^{send}_{wpjt} \leq q_{wpjt} \leq L^{up}_{wpj}\cdot z^{send}_{wpjt} \quad \forall w \in W, p \in P^r, j \in J^r, t \in T \tag{24}$$

$$q_{npt} = \sum_{w}\sum_{j\in j^r} q_{wpjt}\cdot\beta_{wn^rpj} \quad \forall n \in N^r, p \in P^r, t \in T \tag{25}$$

The lower and upper bounds of production capacity limits of technologies type j ($j \in J^{int}$) and $\tilde{j}$ ($\tilde{j} \in \{J^f \cup J^e\}$) in WtE plants are shown in Eqs. (26) and (28). Equation (27) calculates the amount of intermediate product that is produced by waste *w* via technology type j ($j \in J^{int}$) by the conversion rate of $\gamma_{wn^{int}pj}$. Usually, the intermediate products are then converted to final products, or they can be stored for later use. The remaining portion is used as inputs in the production of final products via technology type $\tilde{j}$ $(\tilde{j} \in J^f)$ by the conversion rate of $\theta_{n^{int}n^f p\tilde{j}}$ as indicated in Eq. (29). Since an intermediate can be converted to both final and energy products, the coefficient of $\psi_{n^{int}n^f p\tilde{j}t}$ is used, which is the percentage of intermediate product conversion to the final product in each period, and the rest can be converted to energy products including electricity and heat. For instance, biomass feedstock can be converted into intermediate products such as bio-oil or bio-slurry, before upgrading to the final product of liquid transportation fuels or energy products.

Equation (30) shows that the remaining amount of intermediate product is converted to electricity via technologies type $\tilde{j}$ $(\tilde{j} \in J^e)$ at electricity conversion rate of $\tau_{n^{int}n^{el}p\tilde{j}}$ and conversion efficiency of $\varphi_{n^{int}n^{el}p\tilde{j}}$. Similarly, the amount of produced heat is shown in Eq. (31). If the WtE plant uses a heat only boiler, only electricity will be generated, and in this case $\tau_{n^{int}n^{h}p\tilde{j}}$ will be equal to zero. When in a WtE plant (such as combustion plant) the final products are only heat and electricity, the whole waste can be converted to desired energy products. In this case, $\psi_{n^{int}n^f p\tilde{j}t}$ and $\sum_d \sum_v q_{n^{int}pdvt}$ in that plant are equal to zero. Equation (32) shows the amount of CO_2 emissions from plants operations that exceed the pre-determined emission limit.

$$L_{wpj}^{low} \cdot z_{wpjt}^{send} \leq q_{wpjt} \leq L_{wpj}^{up} \cdot z_{wpjt}^{send} \qquad \forall w \in W, p \epsilon P^e, j \epsilon J^{int}, t \in T \tag{26}$$

$$q_{npt} = \sum_{w} \sum_{j \in J^{int}} q_{wpjt} \cdot \gamma_{wn^{int}pj} \qquad \forall n \in N^{int}, p \epsilon P^e, t \in T \tag{27}$$

$$L_{np\tilde{j}}^{low} \cdot z_{np\tilde{j}t}^{send} \leq q_{np\tilde{j}t} \leq L_{np\tilde{j}}^{up} \cdot z_{np\tilde{j}t}^{send} \qquad \forall n \in N^{int}, p \epsilon P^e, \tilde{j} \epsilon \{J^f \cup J^e\}, t \in T \tag{28}$$

$$q_{npt} = \sum_{n^{int}} \sum_{\tilde{j} \in J^f} \psi_{n^{int}n^f p\tilde{j}t} \cdot q_{n^{int}p\tilde{j}t} \cdot \theta_{n^{int}n^f p\tilde{j}} \qquad \forall n \in N^f, p \epsilon P^e, t \in T \tag{29}$$

where $q_{n^{int}p\tilde{j}t} \leq i_{n^{int}p^e(t-1)} + q_{n^{int}p^e t} - \sum_{d^e} \sum_v q_{n^{int}p^e d^e vt}$

$$q_{npt} = \sum_{n^{int}} \sum_{n^f} \sum_{\tilde{j} \in J^f} \left(1 - \psi_{n^{int}n^f p\tilde{j}t}\right) \cdot q_{n^{int}p\tilde{j}t} \cdot \tau_{n^{int}n^{el}p\tilde{j}} \cdot \varphi_{n^{int}n^{el}p\tilde{j}} \qquad \forall n \in N^{el}, p \epsilon P^e, t \in T \tag{30}$$

$$q_{npt} = \sum_{n^{int}} \sum_{n^f} \sum_{\tilde{j} \in J^f} \left(1 - \psi_{n^{int}n^f p\tilde{j}t}\right) \cdot q_{n^{int}p\tilde{j}t} \cdot \tau_{n^{int}n^{h}p\tilde{j}} \cdot \varphi_{n^{int}n^{h}p\tilde{j}} \qquad \forall n \in N^{h}, p \epsilon P^e, t \in T \tag{31}$$

$$e_{pt}^{oper} \geq \left(\sum_{w} \sum_{j \in \{J^r \cup J^{int}\}} E_{wjp}^{CO_2} \cdot q_{wpjt} \right) - AE_{pt}^{oper} \qquad \forall p \in \{P^r \cup P^e\}, t \in T \tag{32}$$

The total amount of a product type (recycled, intermediate, or final) delivered from a plant to a DC during each period is given in Eq. (33), which is equal to or smaller than the quantity back-ordered in the previous period plus the demand of that product ordered by the DC to the plant. As it was mentioned earlier, the back-ordered amount for intermediates is zero ($b_{n^{int}pdt} = 0$). If total delivered products are smaller than the requested quantity, then the unmet portion will be back-ordered as given in Eq. (34), and should be satisfied in the next period. The total amount of electricity and heat transferred to each city are equal to or smaller than their demands, as given in Eq. (35). The unsatisfied portions of intermediate products, electricity, and heat will be lost, as indicated in Eqs. (36) and (37). Total delivered products to all DCs cannot exceed the number of produced products in each period plus the inventory of products from the previous period, as presented in Eq. (38). Similarly, total transferred electricity and heat to all cities cannot surpass the generated electricity and heat by a WtE plant, as shown in Eq. (39).

$$\sum_{v} q_{npdvt} \leq b_{npd(t-1)} + D_{npdt} \quad \forall n \in \{N^r \cup N^{int} \cup N^f\}, p \in \{P^r \cup P^e\}, d \in \{D^r \cup D^e\}, t \in T \tag{33}$$

$$b_{npdt} \geq \left(b_{npd(t-1)} + D_{npdt}\right) - \sum_{v} q_{npdvt} \quad \forall n \in \{N^r \cup N^f\}, p \in \{P^r \cup P^e\}, d \in \{D^r \cup D^e\}, t \in T \tag{34}$$

$$q_{npct} \leq D_{npct} \quad \forall n \in \{N^{el} \cup N^h\}, p \in P^e, c \in C, t \in T \tag{35}$$

$$l_{npdt} \geq D_{npdt} - \sum_{v} q_{npdvt} \quad \forall n \in N^{int}, p \in P^e, d \in D^e, t \in T \tag{36}$$

$$l_{npct} \geq D_{npct} - q_{npct} \quad \forall n \in \{N^{el} \cup N^h\}, p \in P^e, c \in C, t \in T \tag{37}$$

$$\sum_{d \in \{D^r \cup D^e\}} \sum_{v} q_{npdvt} \leq i_{np(t-1)} + q_{npt} \quad \forall n \in \{N^r \cup N^{int} \cup N^f\}, p \in \{P^r \cup P^e\}, t \in T \tag{38}$$

$$\sum_{c} q_{npct} \leq q_{npt} \quad \forall n \in \{N^{el} \cup N^h\}, p \in P^e, t \in T \tag{39}$$

The initial inventory level of products in each plant is considered to be U_{np}. The inventory balance for recycled and final products is calculated by Eq. (40), which expresses that on-hand inventory and current period production are used to satisfy the current demand and previous back-ordered quantity. Equation (41) indicates the inventory level of intermediate products in each period. The upper limit of inventory level for each type of product in plants is assumed to be S_{np}. Moreover, no heat and electricity storages are considered in this study.

$$i_{npt} = i_{np(t-1)} + q_{npt} - \sum_{d \in \{D^r \cup D^e\}} b_{npd(t-1)} - \sum_{d \in \{D^r \cup D^e\}} D_{npdt} + \sum_{d \in \{D^r \cup D^e\}} b_{npdt} \quad \forall n \in \{N^r \cup N^f\}, p \in \{P^r \cup P^e\}, t \in T \tag{40}$$

$$i_{npt} = i_{np(t-1)} + q_{npt} - \sum_{d \in D^e} \sum_{v} q_{npdvt} - \sum_{\tilde{j} \in \left\{J^f \cup J^e\right\}} q_{np\tilde{j}t} \quad \forall n \in N^{int}, p \in P^e, t \in T \tag{41}$$

There are several worldwide waste control regulations that limit and control the amount of waste every manufacturer can generate during the production process. Equation (42) computes the amount of waste exceeding the waste limit, which incurs a penalty cost paid by the plants.

The first term in Eq. (42) is the amount of waste generated during production of products in plants, which is limited to the pre-determined level of AW_{pt}. The waste produced during the production process and deteriorated waste are disposed to landfills as given in Eq. (43). Equations (44), (45) and (46) compute the number of vehicles required for the transfer of waste and products from plants to landfills, other plants, and DCs respectively. Equation (47) calculates the amount of CO_2 emission incurred by plants' trucks that exceed the emission limit. The bracket in Eq. (47) is the CO_2 emission from transportation, which is limited to the pre-determined level of AE_{pt}^{tran}.

$$w_{pt}^{exc} \geq \left(\sum_{n \in \{N^r \cup N^{int} \cup N^f \cup N^{el} \cup N^h\}} q_{npt} \cdot W_{np} \right) - AW_{pt} \quad \forall p \in \{P^r \cup P^e\}, t \in T \tag{42}$$

$$\sum_l \sum_v q_{plvt} = \sum_{n \in \{N^r \cup N^{int} \cup N^f \cup N^{el} \cup N^h\}} q_{npt} \cdot W_{np} + \sum_w \rho_{wpt} \cdot i_{wp(t-1)} \quad \forall p \in \{P^r \cup P^e\}, t \in T \tag{43}$$

$$y_{plvt} - 1 \leq \frac{q_{plvt}}{L_v} \leq y_{plvt} \quad \forall p \in \{P^r \cup P^e\}, l \in L, v \in V, t \in T \tag{44}$$

$$y_{p\tilde{p}vt} - 1 \leq \frac{\sum_w r_{wp\tilde{p}vt}}{L_v} \leq y_{p\tilde{p}vt} \quad \forall p, \tilde{p} \in \{P^r \cup P^e\} \; and \; p \neq \tilde{p}, v \in V, t \in T \tag{45}$$

$$y_{pdvt} - 1 \leq \frac{\sum_n q_{npdvt}}{L_v} \leq y_{pdvt} \quad \forall p \in \{P^r \cup P^e\}, d \in \{D^r \cup D^e\}, v \in V, t \in T \tag{46}$$

$$\begin{aligned} e_{pt}^{exc} \geq \Bigg(& \sum_l \sum_v D_{pl}^{PL} \cdot y_{plvt} \cdot F_v \cdot E_v^{CO_2} + \sum_{\tilde{p} \in \{P^r \cup P^e\}} \sum_v D_{p\tilde{p}}^{PP} \cdot y_{p\tilde{p}vt} \cdot F_v \cdot E_v^{CO_2} \\ & + \sum_{d \in \{D^r \cup D^e\}} \sum_v D_{pd}^{PD} \cdot y_{pdvt} \cdot F_v \cdot E_v^{CO_2} \Bigg) - AE_{pt}^{tran} \quad \forall p \in \{P^r \cup P^e\}, \& \, p \neq \tilde{p}, t \in T \end{aligned} \tag{47}$$

iv. Distribution centers selling products to cities

The considered DCs are assumed to store products received from different plants, and to redistribute products directly to consumers in different cities. Equation (48) shows the required number of products a DC orders to plants per period based on the current demand. If the demand multiplied by a safety stock coefficient is smaller than the on-hand inventory, then r_{ndt} will be equal to zero. The demand of recycled and final products is the cumulative demand received from all cities as $\sum_c D_{ndct}$. Since there is a possibility that a manufacturer fails to deliver the products at the required time, or the delivered products' quality might be substandard, the DC orders more than the required amount as the safety stock (ε_{ndt}), and ε_{ndt} should be greater than one. Equation (49) presents the delivered products to a DC by all plants.

$$r_{ndt} \geq (\varepsilon_{ndt} \cdot D_{ndt}) - i_{nd(t-1)} \quad \forall n \in \{N^r \cup N^{int} \cup N^f\}, d \in \{D^r \cup D^e\}, t \in T \tag{48}$$

$$q_{ndt} = \sum_{p \in \{P^r \cup P^e\}} \sum_{v} q_{npdvt} \quad \forall n \in \{N^r \cup N^{int} \cup N^f\}, d \in \{D^r \cup D^e\}, t \in T \tag{49}$$

The total amount of products delivered from a DC to a city is given in Eq. (50), which is equal to or smaller than the quantity back-ordered in the previous period plus the demand of product ordered by a city to the DC in the current period. If total transported products is less than the demanded amount, the unsatisfied portion will be back-ordered as given in Eq. (51), and should be fulfilled in the next period. The amount of unsatisfied demand of products received by cities in period t is zero if the amounts of demand in period t plus the back-order quantity from previous period are met by the inventory from the previous period and the total quantity of products transferred to the DC in the current period. It is assumed that back-ordering of products in DCs are allowed, but the DC does not pay penalty cost for the delay in demand fulfillment. Equation (52) indicates that the total number of products delivered to cities cannot exceed the total number of products shipped to DCs in the current period plus the on-hand inventory from the previous period. Equations (53) and (54) show the total number of products distributed to each city during each period. Equation (55) presents the total received intermediate products in DCs. The initial inventory level of products in each DC is assumed to be U_{nd}. Inventory levels of recycled and final products in DCs are shown in Eqs. (56) and (57), and the upper limit of inventory level in a DC is considered to be S_{nd}.

$$\sum_{v} q_{ndcvt} \leq b_{ndc(t-1)} + D_{ndct} \quad \forall n \in \{N^r \cup N^f\}, d \in \{D^r \cup D^e\}, c \in C, t \in T \tag{50}$$

$$b_{ndct} \geq \left(b_{ndc(t-1)} + D_{ndct}\right) - \sum_{v} q_{ndcvt} \quad \forall n \in \{N^r \cup N^f\}, d \in \{D^r \cup D^e\}, c \in C, t \in T \tag{51}$$

$$\sum_{c} \sum_{v} q_{ndcvt} \leq i_{nd(t-1)} + q_{ndt} \quad \forall n \in \{N^r \cup N^f\}, d \in \{D^r \cup D^e\}, t \in T \tag{52}$$

$$q_{nct} = \sum_{d \in \{D^r \cup D^e\}} \sum_{v} q_{ndcvt} \quad \forall n \in \{N^r \cup N^f\}, c \in C, t \in T \tag{53}$$

$$q_{nct} = \sum_{p \in P^e} \sum_{v} q_{npct} \quad \forall n \in \{N^{el} \cup N^h\}, c \in C, t \in T \tag{54}$$

$$q_{ndt} = \sum_{p \in P^e} \sum_{v} q_{npdvt} \quad \forall n \in N^{int}, d \in D^e, t \in T \tag{55}$$

$$i_{ndt} = i_{nd(t-1)} + q_{ndt} - \sum_{c} b_{ndc(t-1)} - \sum_{c} D_{ndct} + \sum_{c} b_{ndct} \quad \forall n \in \{N^r \cup N^f\}, d \in \{D^r \cup D^e\}, t \in T \tag{56}$$

$$i_{ndt} = i_{nd(t-1)} + q_{ndt} - \sum_{d} D_{ndt} \quad \forall n \in N^{int}, d \in D^e, t \in T \tag{57}$$

The number of vehicles required for delivering the final and recycled products from DCs to cities is given in Eq. (58). Equation (59) calculates the amount of CO_2 emission incurred by DCs's vehicles that exceed the emission limit.

$$y_{dcvt} - 1 \leq \frac{\sum_n q_{ndcvt}}{L_v} \leq y_{dcvt} \quad \forall d \in \{D^r \cup D^e\}, c \in C, v \in V, t \in T \tag{58}$$

$$e_{dt}^{exc} \geq \left(\sum_c \sum_v D_{dc}^{DC} \cdot y_{dcvt} \cdot F_v \cdot E_v^{CO_2} \right) - AE_{dt}^{tran} \quad \forall d \in \{D^r \cup D^e\}, t \in T \tag{59}$$

***v. Waste transfer to landfills*:**

A landfill receives any useless MSW from different separation centers and plants as shown in Eq. (60). Municipal waste landfills receiving a mixture of MSW have limited disposal capacity, where the waste received from all waste separation centers during period *t* should not exceed its capacity ($q_{lt} \leq LC_{lt}$). Decomposition of solid waste in landfills generates a considerable amount of CH_4 emission. Equation (61) shows the CH_4 emissions emitted from landfills that exceed the emission limits (AE_{lt}^{land}). It is assumed that CH_4 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.

$$q_{lt} = \sum_s \sum_v q_{slvt} + \sum_{p \in \{P^r \cup P^e\}} \sum_v q_{plvt} \quad \forall l \in L, t \in T \tag{60}$$

$$e_{lt}^{exc} \geq (E^{CH_4} \cdot q_{lt}) - AE_{lt}^{land} \quad \forall l \in L, t \in T \tag{61}$$

Computational Results

In this section, we provide a numerical example in order to illustrate the application of the proposed mathematical model. Through this example, we show that how the developed optimization model is able to identify the optimal processing route for the best utilization and management of MSW. The considered multi-level SC problem consists of two cities as waste sources and consumer locations, two separation centers, two recycling plants with two DCs for selling the recycled products, three WtE plants with two DCs for selling intermediate and final products, and two landfills, as presented in Figure 1. The suggested integrated recycling and WtE SC network incorporates all the functions in such a way that the waste is collected and transferred, and products are manufactured and distributed at the right place and right time, and the anticipated demands are fulfilled along with maximizing the total profit of the entire network.

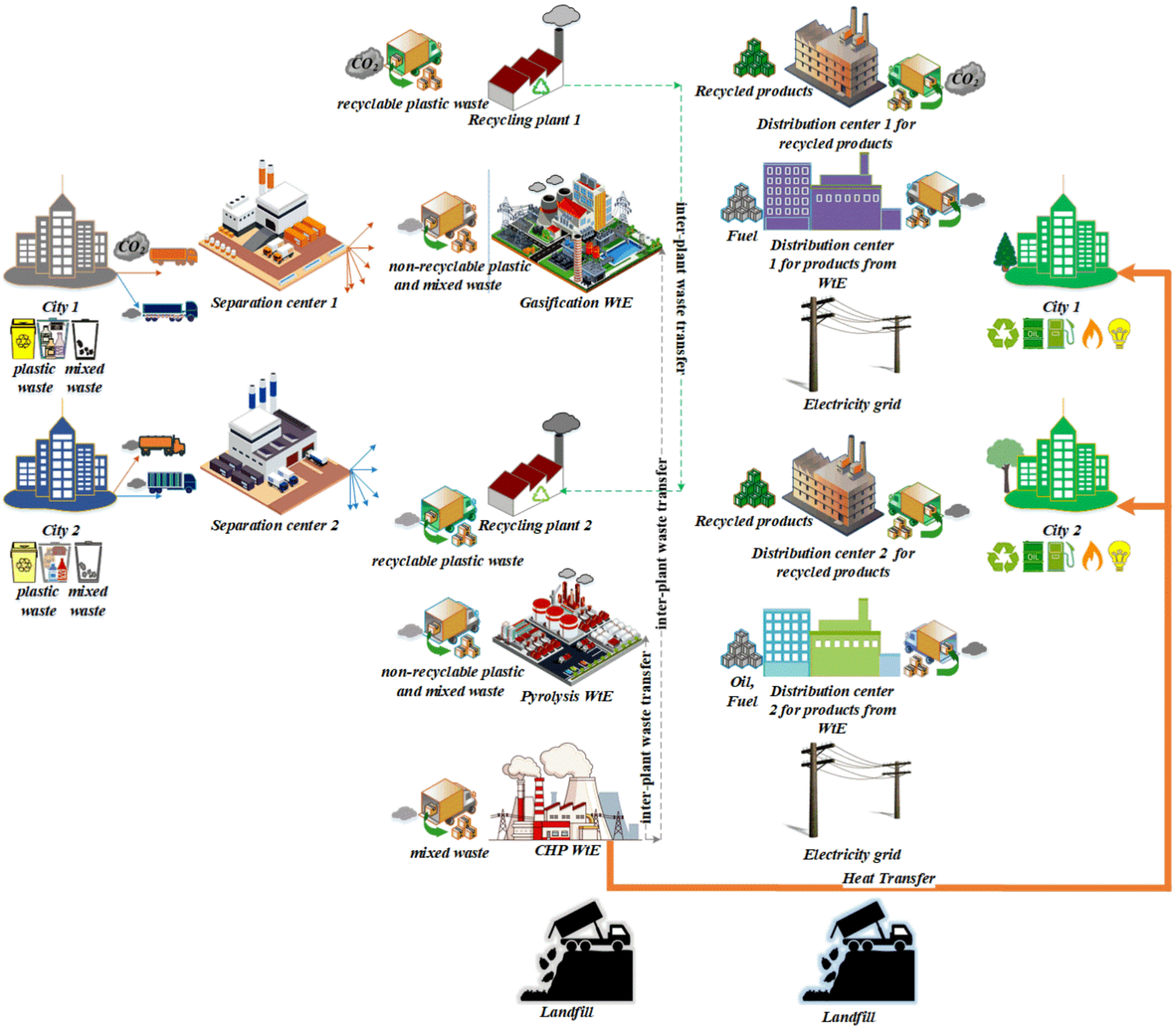

Figure 1. A schematic representation of the addressed waste SC problem (some of the icons presented in this diagram are created by Iconicbestiary - Freepik.com)

The considered MSW is categorized into various fractions as mixed waste and six types of plastic waste including polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), polyethylene (PE), high-density polyethylene (HDPE), and low-density polyethylene (LDPE). It is assumed that mixed waste is non-recyclable and it is processed only in WtE plants, but plastic waste can be used in both recycling and energy recovery processes. The data for the annual waste production amounts, technologies to process the waste, conversion factors, type of produced products, and selling prices of products are taken from Santibañez-Aguilar et al.[15,25]. Total MSW generation is roughly 2,910 million kg during a year in two cities. The proportion of PET waste is 0.03 % of the total produced waste, followed by LDPE (0.03 %), HDPE (0.11 %), and PS (0.22 %). The PP, non-recyclable mixed waste, and PE constitute the highest portion of the waste with 4.79 %, 34.84 %, and 59.98 %, respectively.

Figure 2 shows the percentage of each waste type transferred for landfilling, recycling, and energy recovery based on the optimization results. The details of processing technologies in each plant, produced products, and conversion factors are also presented in Figure 2. Overall, during a year, the value of waste planned for energy recovery amounted to 1,037.24 million kg, which is around 36 % of the total produced waste. The total amount of recyclable waste was 730.33 million kg, which corresponds to 25 % of the total generated waste, and almost 39 % of the total waste ended up in the landfills.

Considered waste types can be converted into different forms of products including carbon nanotubes, pellets, paraffins, olefins, biofuels, electricity, and heat in recycling and WtE plants. The demand data for the products and their selling prices in two cities are provided in Table 1. The planning horizon is one year and the length of the time period used in the computational experiments is one week. However, for the sake of simplifying the discussion, the model analysis is conducted seasonally and monthly.

Table 1. Seasonal demand of products and their prices

City	Product	Winter	Spring	Summer	Fall	Total	Price
1	Nanotube 140 µm	103,372.12 kg	87,655.16 kg	95,392.80 kg	83,425.74 kg	369,845.81 kg	100 USD/kg
1	Nanotube 252 µm	306,814.57	277,975.45	307,373.00	262,888.62	1,155,051.64	70
1	Pellet	87,509.73	143,571.81	142,971.78	107,459.74	481,513.07	0.36
1	n-Paraffins	20,027.47	20,525.59	21,345.28	20,744.60	82,642.94	0.66
1	n-Olefins	14,296.88	14,469.17	15,034.03	14,613.71	58,413.79	0.18
1	1-Olefins	21,954.29	22,218.45	23,134.06	22,474.59	89,781.39	0.61
1	Branched Paraffins	40,100.93	40,596.95	42,265.51	41,066.83	164,030.21	0.31
1	Gasoline	71,909.88	72,588.30	74,724.23	72,788.52	292,010.93	[0.57-0.65]
1	Diesel	377,719.55	410,082.46	349,757.94	453,956.50	1,591,516.45	[0.64-0.76]
1	Heavy oil	32,561.15	33,601.16	32,801.11	34,723.49	133,686.91	[0.39-0.51]
1	Ethanol	308,027.56	312,297.34	326,492.91	311,313.02	1,258,130.84	0.54
1	Heat	308,983.32 MWh	272,612.15 MWh	244,714.03 MWh	308,919.85 MWh	1,135,229.35 MWh	75 USD/MWh
1	Electricity	246,608.90 MWh	195,368.03 MWh	246,589.93 MWh	217,618.10 MWh	906,184.95 MWh	140 USD/MWh
2	Nanotube 140 µm	92,490.84 kg	78,428.30 kg	85,351.45 kg	74,644.08 kg	330,914.67 kg	100 USD/kg
2	Nanotube 252 µm	274,518.30	248,714.87	275,017.95	235,216.13	1,033,467.25	70
2	Pellet	78,298.18	128,458.99	127,922.12	98,192.65	432,871.95	0.36
2	n-Paraffins	17,919.32	18,365.00	19,098.41	18,560.96	73,943.69	0.66
2	n-Olefins	12,791.94	12,946.10	13,451.50	13,075.43	52,264.97	0.18
2	1-Olefins	19,643.31	19,879.66	20,698.89	20,108.84	80,330.72	0.61
2	Branched Paraffins	35,879.78	36,323.59	37,816.51	36,744.00	146,763.87	0.31
2	Gasoline	64,340.42	64,947.43	66,858.52	65,126.57	261,272.93	[0.57-0.65]
2	Diesel	379,302.99	355,428.31	202,311.72	503,503.73	1,440,546.75	[0.64-0.76]
2	Heavy oil	30,684.19	30,101.72	23,190.07	35,768.87	119,744.86	[0.39-0.51]
2	Ethanol	275,603.61	279,423.94	292,125.23	278,543.23	1,125,696.01	0.54
2	Heat	463,474.98 MWh	408,918.23 MWh	367,071.04 MWh	463,379.77 MWh	1,702,844.02 MWh	75 USD/MWh
2	Electricity	369,913.34 MWh	293,052.04 MWh	369,884.90 MWh	326,427.14 MWh	1,359,277.43 MWh	140 USD/MWh
DC 3	Pyrolysis oil	12,800,737.53 kg	11,293,927.63 kg	12,798,108.02 kg	10,138,152.61 kg	47,030,925.79 kg	0.59 USD/kg

The proposed MILP model is formulated and solved using GAMS/CPLEX (v.24.9.1) on a laptop with an Intel Core i5/2.40 GHz and 8 GB of RAM. The model includes 174,992 constraints, 166,048 continuous variables, 9,620 integer and 24,908 binary variables with the solution time of CPLEX 56.6 seconds and total execution time of GAMS 204.4 seconds, including the data processing from/to Excel sheets.

The measurement of the economic factor for the applied model is based on the calculation of the total net profit of the SC network. The model produces an annual net profit of 19.45 MUSD. The network total cost is 766.09 MUSD, which comprises the production cost (49.95 %), collection cost (15.19 %), transportation cost (12.02 %), separation cost (8.74 %), landfilling cost (7.32 %), back-ordering cost (5.71 %), emission cost (0.81 %), inventory cost (0.17 %), and waste production cost (0.09 %). The total annual revenue obtained from selling the products is 785.54 MUSD. The proportion of each product in revenue generation is shown in Table 2.

Table 2. Production quantity by each type of waste and proportion of each product to annual revenue

Waste type	**Product type**	**Production quantity**	**Revenue**	**Proportion to total revenue**
PET	Nanotube 140 μm	75,832.39 kg	7,583,238.54 USD	0.965%
PP	Nanotube 140 μm	80,652.74	8,065,274.33	1.027%
PE	Nanotube 140 μm	544,275.36	54,427,535.71	6.929%
PE	Nanotube 252 μm	1,088,730.71	76,211,149.99	9.702%
PP	Nanotube 252 μm	1,099,788.17	76,985,172.21	9.800%
PP	Pellet	240,657.92	86,636.85	0.011%
PS	Pellet	262,297.94	94,427.26	0.012%
PE	Pellet	411,429.16	148,114.50	0.019%
LDPE	n-Paraffins	50,027.84	33,018.37	0.004%
HDPE	n-Paraffins	106,558.79	70,328.80	0.009%
HDPE	n-Olefins	110,678.76	20,608.27	0.003%
LDPE	l-Olefins	46,470.05	28,346.73	0.004%
HDPE	l-Olefins	123,642.05	75,421.65	0.010%
PP	Branched Paraffins	310,794.09	96,346.17	0.012%
PE	Gasoline	233,613.28	141,956.79	0.018%
PS	Gasoline	319,670.58	196,377.83	0.025%
PE	Diesel	69,537.06	47,791.15	0.006%
PS	Diesel	181,304.44	124,982.76	0.016%
PP	Diesel	2,781,221.69	1,929,861.08	0.246%
PE	Heavy oil	53,129.44	23,555.95	0.003%
PS	Heavy oil	200,302.33	89,711.85	0.011%
PE	Ethanol	2,383,826.85	1,290,968.49	0.164%
Mixed Waste	Heat	2,838,073.37 MWh	212,855,502.74	27.097%
LDPE	Electricity	335.41 MWh	46,957.15	0.006%
HDPE	Electricity	1,108.33 MWh	155,166.77	0.020%
pp	Electricity	1,393.56 MWh	195,098.22	0.025%
PS	Electricity	1,444.18 MWh	202,185.27	0.026%
Mixed Waste	Electricity	2,261,180.90 MWh	316,565,325.85	40.299%
Mixed Waste	Pyrolysis oil	47,030,925.79 kg	27,748,246.22	3.532%

It is apparent from Table 2 that the non-recyclable mixed waste is the most valuable waste category, which contributed to 70.93 % of revenue generation. The majority of revenue is generated from electricity and heat sales, which accounted for 40.38 % and 27.10 % of the total revenue, respectively. In terms of recycling, 252 μm and 140 μm nanotubes led to 19.50 % and 8.92 % of revenue growth. Table 2 also indicates that PE is the best plastic waste for production of 140 μm nanotube, pellet, and ethanol, and PP produced the highest amount of 252 μm nanotube and diesel. As for the polyolefin plastic type, HDPE produced the highest n-Paraffins, l-Olefins, and n-Olefins, compared to LDPE. From the results presented in Table 2 and demand data in Table 1, it can be seen that all the products demands are fulfilled.

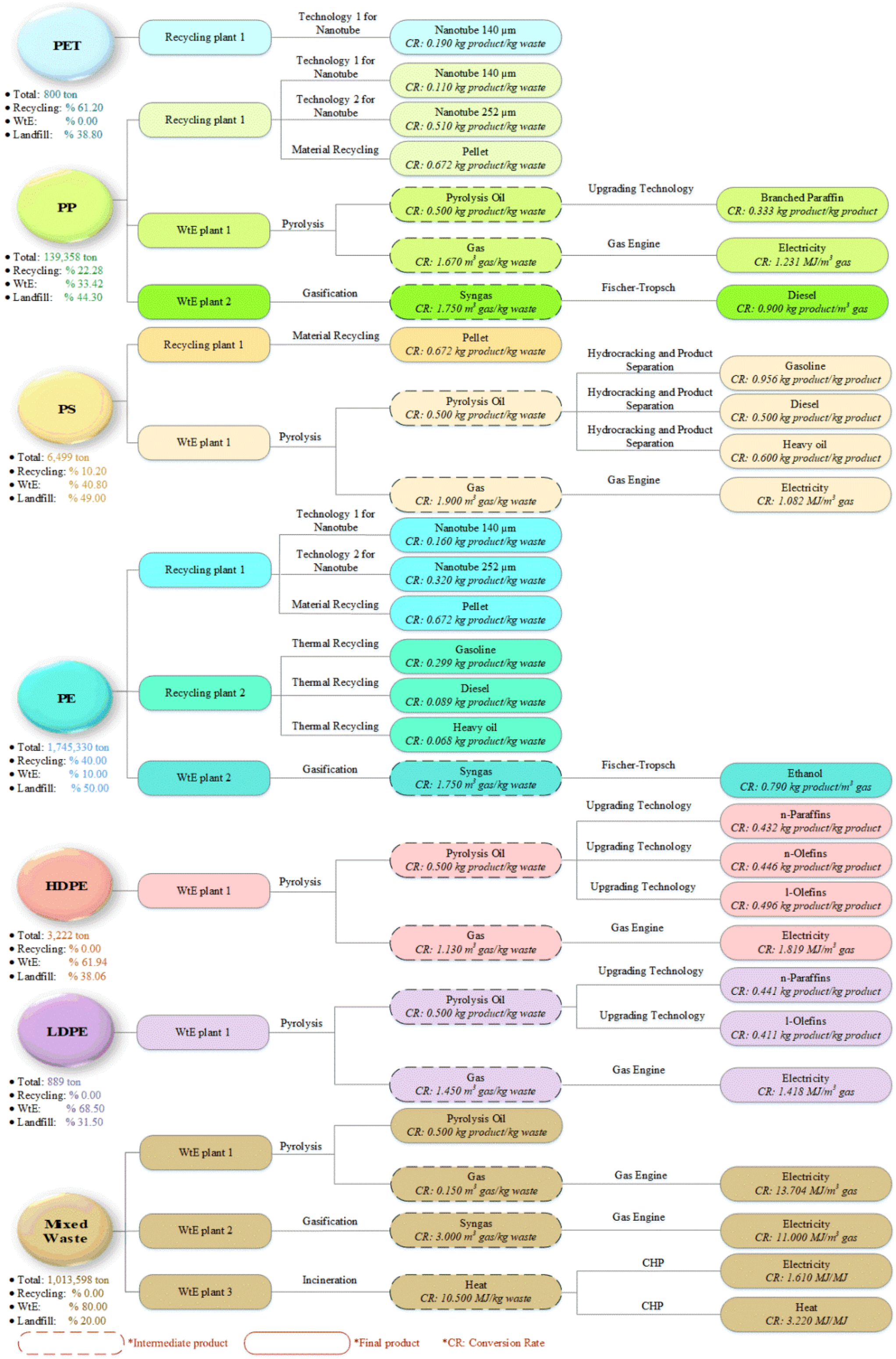

Figure 2. Structure of waste allocation and product types in the recycling and WtE plants

The results also show that production of nanotubes, pellets, gasoline, diesel, and heavy oil in recycling plants contributed to 224 MUSD (28.49 % of total profit). This implies that it is more profitable to recycle the recyclable waste (PET, PP, PE, and PS) first, and then treat the rest of the waste for energy recovery. Therefore, not only the integration of recycling with the waste treatment technologies is economically viable, but also in-line with the common European Union WM policy and waste hierarchy, where recycling is preferred over energy recovery.

In order to assess the impact of the electricity and heat price changes on the net profit, a sensitivity analysis is performed. As shown in Figure 3, the model profit is greatly affected by the reduction of heat and electricity prices. Reducing the electricity price from 140 to 130.2 USD/MWh (7 % reduction) yields the negative profit of – 1.90 MUSD, and if the electricity price is decreased by 6.40 % and all other assumptions remain the same, the considered SC network will have a zero profit. As for heat, decreasing its price from 75 to 67.85 USD/MWh (9.53 % reduction) produces a profit of zero. Furthermore, a sensitivity analysis of price reduction of 252 μm nanotube indicated that its impact on the total profit is slightly lower than the heat and electricity price reduction, as 13.25 % decrease in 252 μm nanotube price (60.72 USD) drops the economic profit to zero.

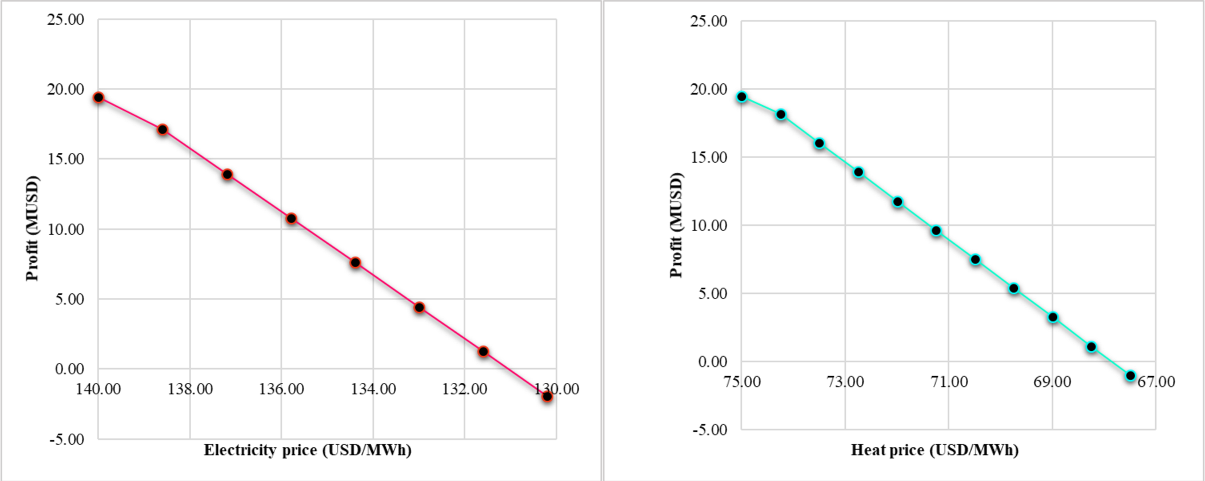

Figure 3. Sensitivity analysis of electricity/heat price reduction rates to annual profit

Within the established schedule for the production amount of final products (based on the demand received from different DCs), the requirements for intermediate products and the waste needed in the production of the intermediate products can be identified. WtE plants are generally multi-stage systems, as there is a parent-component relationship between their products. In this case, the output of one stage is the input for the next stage. In such production systems, end products (e.g. diesel, gasoline, and heavy oil) are produced from the intermediate products (e.g. pyrolysis oil). Besides, an intermediate product might be a final product for one plant and an input for another plant. For instance, WtE plant 2 produces pyrolysis oil from mixed waste and sells it at a DC, but uses the pyrolysis oil yielded from HDPE and LDPE as the raw material to produce the final products such as n-paraffins, n-olefins, 1-olefins, and branched paraffins. In this case, a precise planning for the inventory management of the intermediate products is required as they need to be taken out when they are required to undergo the process of their conversion into the final products. Moreover, to keep the inventory cost of semi-finished products low, the right amount of intermediate product should be produced, because in-process inventory is usually of no use until it is transformed into the final product. Figure 4 illustrates the SC planning for the production of gasoline, diesel, heavy oil, and ethanol demanded by the considered cities. As it is shown, the gasoline is produced from PS (WtE plant 1) and PE (recycling plant 2), and diesel is made from PE (recycling plant 2), PS (WtE plant 1), and PP (WtE plant 2). Besides, heavy oil is obtained from PE (recycling plant 2) and PS (WtE plant 1), and ethanol is produced from PE (WtE plant 2). The objective is to optimally distribute these waste types from each city to each separation center (only the usable portion is shown in Figure 4) and from separation centers to the recycling and WtE plants so that the demanded products can be produced at the required time and quantity. The profit obtained from selling the gasoline, diesel, heavy oil, and ethanol is 3.85 MUSD.

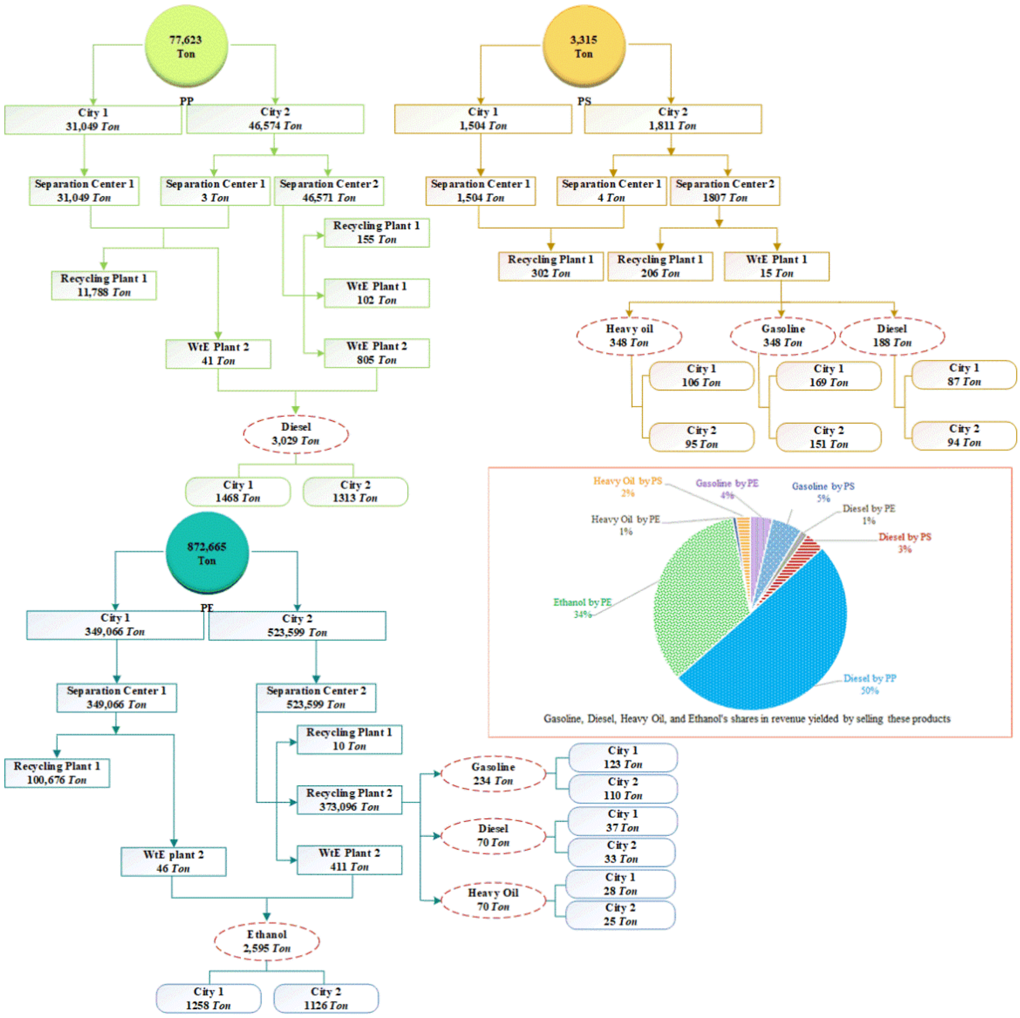

Figure 4. Supply chain planning for the production of fuel products

The plants order the waste from the separation centers based on the demand of the final product and their waste inventory at hand. For instance, to produce diesel, PP waste is distributed from city 1 to separation center 1 and from city 2 to separation centers 1 and 2. PP is then processed in WtE plant 2 using Fischer-Tropsch synthesis to make diesel. On the other hand, PE is also transferred to recycling plant 2 to produce diesel through thermal recycling. Each waste to product conversion is subject to unique logistics depending on feedstock types, conversion technologies, production and storage capacities, output types and distribution mode. It is worth to mention that full utilization of the total transferred waste is not possible since each waste has a specified rate for the usage and conversion to useful products.

Pyrolysis, gasification, and CHP plants process the non-recyclable waste to generate electricity and heat demanded by two cities. Figure 5 presents the amount of generated electricity by these WtE plants. In this paper, it is assumed that heat and electricity are produced together in a CHP plant. This process, which captures and uses the waste heat created during electricity production, is most cost-effective when there is a constant heat demand, e.g. adjacent industrial plants or district heating systems. Operation of CHP plants generally depends on the heat demand and afterward, the range of electricity generation is determined; i.e. the more heat is produced the less energy is available for electricity production. In the CHP plant, the waste as fuel is converted into bottom ash, flue gases, particles, and high-temperature heat (Eq. (27)). Heat produced by combustion of waste creates steam that drives a turbine to generate electricity (Eq. (30)).

Unlike incineration, gasification does not generate energy from waste through direct combustion. In gasification, the waste, steam, and O_2 are fed into a gasifier where heat and pressure break apart the chemical bonds of the waste to form the intermediate product of synthesis gas or syngas (carbon monoxide (CO), CH_4, Nitrogen (N_2), H_2, and CO_2) (Eq. (27)). Then, the produced syngas can be used to produce energy through combustion (Eq. (30)), or turned into a wide range of end-products including transportation fuels, chemicals, fertilizers, H_2, and substitute natural gas (Eq. (29)). Pyrolysis, depending on the operating conditions of temperature and residence time (slow, fast, ultra-fast or ablative pyrolysis) can produce varying quantities of products such as char, pyrolysis oil, and syngas (CO, CH_4, H_2, CO_2, and hydrocarbons) (Eq. (27)), all of which can be sold as fuels (Eq. (29)). Then, gas or oil can be used as fuel for firing the boiler for steam production and subsequent power production (Eq. (30)). It is assumed that energy efficiency for CHP, gasification, and pyrolysis are 85 %, 75 %, and 75 %, respectively.

As demonstrated in Figure 5, pyrolysis has the lowest economic potential because the smallest amount of electricity was produced by this plant (50,414 MWh/year), meeting the 2.23 % of electricity demand, followed by gasification, which produced 739,251 MWh in a year (32.63 % of demand). The CHP achieves the highest energy efficiency, in which it generated 1,475,798 MWh of electricity during a year. Evidently, CHP led to a more profitable conversion technology, and electricity production from non-recyclable waste is more profitable than plastic waste feedstock.

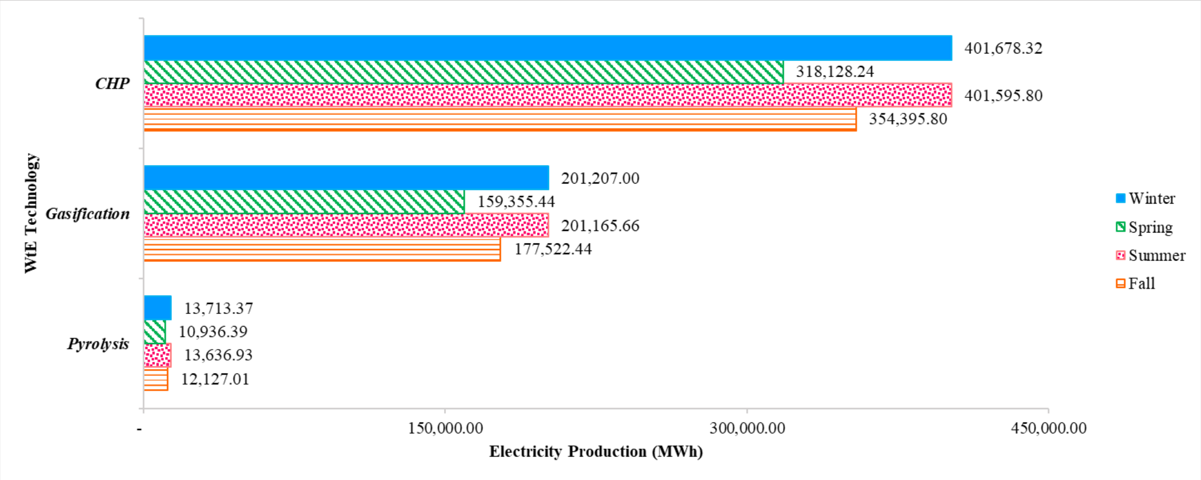

Figure 5. Production of electricity by pyrolysis, gasification, and CHP plants

Though plastic waste can be converted into energy since it has a significant calorific value, it is mostly turned into pyrolysis oil, which is then upgraded to fuels and other useful products. It justifies the reason for the lower electricity generation by pyrolysis compared to other two technologies. Using the plastic waste as the fuel source in pyrolysis plant, LDPE produced the smallest quantity of electricity (0.015 % of electricity demand), and PP and PS contributed to a relatively higher energy production compared to other plastic waste (0.064 % and 0.062 % of total electricity generation, respectively). CHP and gasification used only mixed waste as their fuel to produce electricity. Besides, the energy in the mixed waste is utilized and supplied as heat in the CHP plant, in addition to producing electricity that is transferred to the grids, as shown in Figure 6. Eventually, the CHP plant satisfies more than 65 % of electricity demand and 100 % heat demand. It should be noted that pyrolysis and gasification are very promising technologies in terms of clean energy production and having lower negative environmental impacts, whereas CHP led to the production of higher CO_2 emissions compared to other WtE technologies (38.63 Mkg CO_2/year).

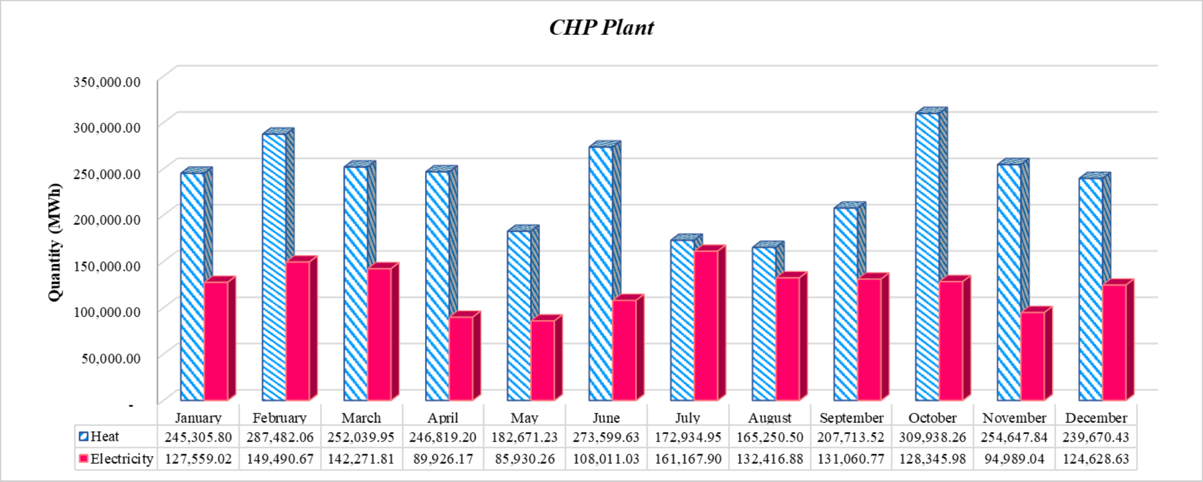

Figure 6. Monthly heat and electricity production by the CHP plant

In addition to the economic evaluation of the considered SC network, the proposed model is also analyzed by measuring the emission from transportation. Table 3 shows the data related to trucks used for transportation of waste and products among all SC entities, time and distance-dependent costs, and the considered CO_2 emissions from transportation.

Table 3. Components of transportation cost

Vehicle type	Loading capacity (ton)	Fuel consumption (l of fuel/km)	CO_2 emissions (kg CO_2/l of fuel)	Average speed (km/h)	Fuel price (USD/l)	Distance-dependent cost (USD/km)	Time-dependent cost (USD/hr/truckload)	Fixed transportation costs (USD)
Truck 1	10.0	0.300	2.68	56	1.147	0.44	19	100
Truck 2	12.5	0.313	2.68	64	1.147	0.46	20	150
Truck 3	14.0	0.357	2.68	72	1.147	0.52	21	200

Finding the optimum level for waste and product transfers during each period among all the entities of SC network resulted in determining the optimal number of vehicles required for delivery, and thus obtaining the lowest transportation cost considering the environmental effects. Accordingly, during a year 411,734 trips using truck type 1, 131,460 trips by truck type 2, and 367 trips via truck type 3 were carried out within all the entities of the SC network. In order to assess the transportation cost according to a function of the quantity of materials transferred, Eq. (62) is used, which is the modified transportation cost function under the all-unit discount policy.

$$TC_{new} = TC - \omega \cdot \left(\sum_{w,s,p \in \{p^r, p^e\}, v, t} q_{wspvt} - B^{SP} \right) \tag{62}$$

where ω is the discount coefficient and it is assumed to be 0.01, and B^{SP} is the breakpoint used for the lot-size transferred from separation centers to the plants. According to Eq. (62), if the shipment volume is less than the breakpoint, then the plant will not receive a discount, and adversely, it will be entitled to extra payment. Figure 7 indicates that how a specific discount breakpoint affects the transportation cost. It is assumed that the breakpoint is 20,000 kg for recycling plants and 40,000 kg for the WtE plants. When the breakpoints are enabled, the total transportation cost reduces by 15.13 MUSD/year, and total waste transferred to recycling and WtE plants increases by 51,847 tons and 19,669 tons per year, respectively.

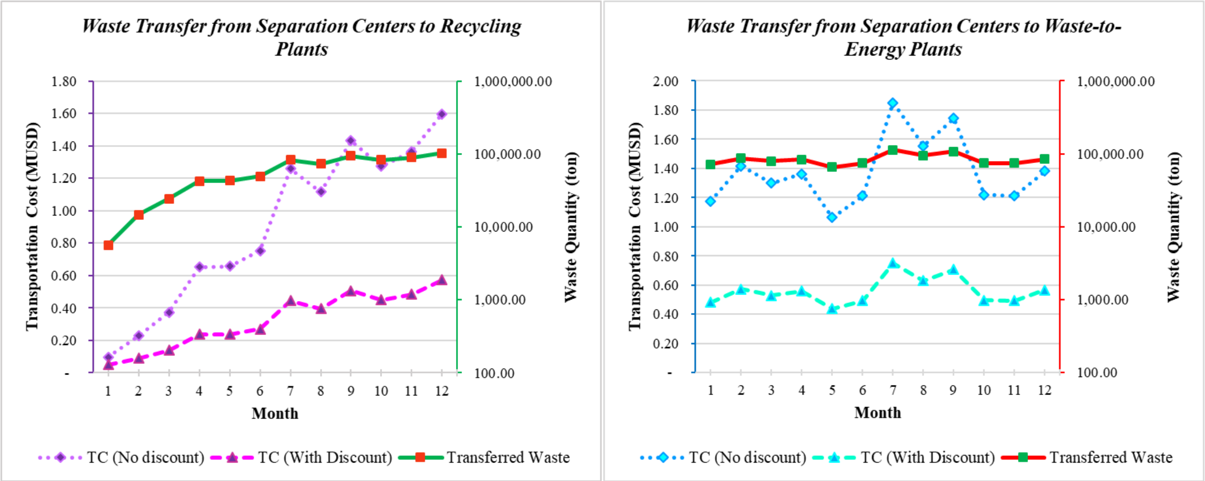

Figure 7. Comparison of actual transportation cost (no discount) with discounted cost

Figure 8 shows that how changing breakpoints impacts the reduction of transportation cost. It can be seen that the transportation cost and shipment quantity are not significantly affected by the large discount rates since based on the proposed model the orders greater than a specific level cannot be executed. It can be due to the imposed ordering limits, where plants order the waste based on their demand requirements, on-hand waste inventory, and storage and production capacities.

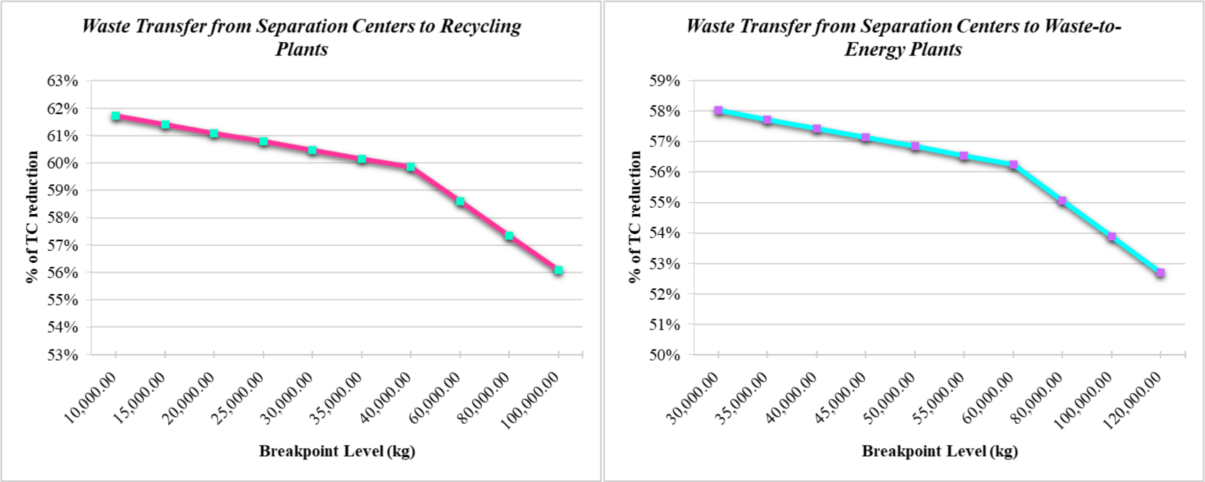

Figure 8. Effect of different breakpoints on the reduction of transportation cost

Finally, a sensitivity analysis is conducted for the CO_2 emission level against the profit and transportation cost of the whole SC network. When the emission constraints for all levels of the SC network are relaxed, as expected, the maximum profit was yielded (25.80 MUSD). In this case, the model priority is meeting the customers' demands, as well as minimizing the transportation and back-ordering costs. Thereafter, we tightened the right-hand side of emission constraint by different values from 2,000 to 16,000 kg CO_2 in every period to analyze the impact of the CO_2 emission level on the transportation cost, as well as the profit. The results are depicted in Figure 9.

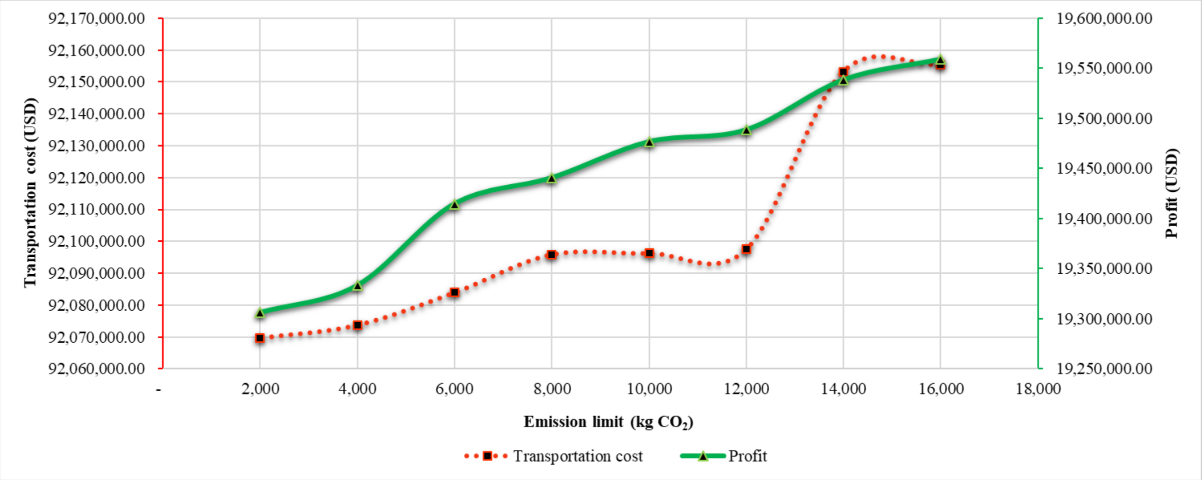

Figure 9. Effect of CO_2 emission limitation on the profit and transportation cost

When the upper limit for CO_2 emission levels is set to 16,000, the profit drops remarkably from 25.80 M€ to 19.56 M€ (24.19 % reduction). It can be due to the fact that now the tradeoff is also between the emission and transportation cost. The more the limitation is tightened, the profit declines gradually with a roughly fixed slope as the emission cost is increasing. Dropping the emission limit to 2,000 kg CO_2 (87.5 % reduction) will drop the profit by 1.29 %. It also resulted in the reduction of the total number of trips during a year, where total trips decreased from 543,561 to 543,479. Tightening the emission limit causes the transportation cost decrease with an increasing slope as the model tries to decrease the transportation frequencies to avoid exceeding the emission limit, but it also may increase the back-ordering cost. It should be noted that these policies depend on the decision-makers to make a tradeoff between the environmental effects and high risk of unfulfilling demand.

Conclusions

For the optimal planning of a WtE system, it is crucial to consider the modern and integrated concept of SCs. A robust waste SC network should be compliant and flexible in order to cope with the fluctuations in the market demand and waste availability. In this paper, an MILP model is developed for the optimization of a multi-echelon, multi-period, and multi-product WM system. The presented SC considers the individual elements and companies (waste, supplier, manufacturer, distributor, and consumer) within the organization as integrated units. The proposed model covers three dimensions of sustainability by considering the economic factor for maximizing the total SC profit, social factor by meeting the demand that leads to customer satisfaction and the environmental factor by considering the emissions from the transportation, production processes, and landfills. The purpose of this study is to find a balance between SC costs, waste reduction, and using the waste efficiently, as well as ensuring environmental sustainability in the planning and operations of SC entities, and continuous feedstock supply.

The formulation focuses on determining the optimal quantity of each waste type supplied from each potential waste source to each separation center and then to the corresponding processing plants, the amount of waste transferred to different technologies, and quantity and types of generated products sent from plants to DCs and finally to the markets. Besides, the model considers the available operational capacities including the inventory storage capacities, and the capacity of the recycling and WtE technologies including CHP, pyrolysis, and gasification. The presented MILP model was solved efficiently in a reasonable computational time using GAMS. Based on the optimized results, the operation and logistics management of the waste were determined, and the best configuration of the SC was attained. The model identified the best feedstock combination, inventory levels, number of transportation vehicles, conversion processes and yielded products while maximizing the overall SC profit.

The applicability of the proposed system was illustrated through a numerical example with two waste collection points, two separation centers, two recycling and three WtE plants, four DCs, two waste disposal sites, and two consumer locations. Furthermore, sensitivity analyses were performed to investigate the effects of the fluctuations in the prices of the most significant products (heat and electricity), as well as the emission limits on the optimization results. It was shown that the profit of the proposed SC is highly affected by the changes in heat and electricity prices. Moreover, it was found that tightening the emission limits results in profit reduction due to increase in emission penalty cost and back-ordering cost, as well as reduction of transportation cost due to the decrease in the number of transportation trips.

It was shown that among different types of plastic and mixed waste, the energy recovery from non-recyclable mixed waste had a significant contribution to the economy. However, recycling was also a profitable WM option, as the production of nanotubes from plastic waste had a noticeable effect on profit as well. The most obvious finding to emerge from this study is that the capability of the waste SC is highly affected by the level of coordination and incorporation between the entities involved in the SC, together with the efficient flow of waste materials. The current study has only examined the deterministic SC network, and the uncertainty in the model's parameters was not taken into account. More broadly, research is also needed to incorporate the uncertainty into the waste SC management, and enhance the model with techniques dealing with uncertainty in various parameters involved in the WM systems.

Notation

Indices:

w	Waste type, $w \in W$
c	Waste collection center (city), $c \in C$
s	Waste separation center, $s \in S$
l	Landfill, $l \in L$
p	Recycling and WtE plants, $p \in \{P^r \cup P^e\}$
d	DC selling products from recycling and WtE plants, $d \in \{D^r \cup D^e\}$
j	Waste processing technology, $j \in \{J^r \cup J^{int}\}$
J^r	Waste processing technology to produce recycled products in recycling plants
J^{int}	Waste processing technology to produce intermediate products in WtE plants
$\tilde{j}$	Intermediate product processing technology to produce final and energy products, $\tilde{j} \in \{J^f, J^e\}$
J^f	Technology producing final product in WtE plant
J^e	Technology producing heat and electricity in WtE plant
n	Produced product in recycling and WtE plants, $n \in \{N^r \cup N^{int} \cup N^f \cup N^{el} \cup N^h\}$
N^r	Recycled product in recycling plant
N^{int}	Intermediate product in WtE plant
N^f	Final product in WtE plant
N^{el}	Electricity in WtE plant
N^h	Heat in WtE plant
v	Transportation vehicle, $v \in V$
t	Time period, $t \in T$

Parameters:

AE_{dt}^{tran}	Allowed CO_2 emission level from transportation by DC d in period t (kg CO_2)
AE_{lt}^{land}	Allowed CH_4 emission level for landfill l in period t
AE_{pt}^{oper}	Allowed CO_2 emission level from plant operations by plant p in period t (kg CO_2)
AE_{pt}^{tran}	Allowed CO_2 emission level from transportation by plant p in period t (kg CO_2)
AE_{st}^{tran}	Allowed CO_2 emission level from transportation by separation center s in period t (kg CO_2)
AW_{pt}	Allowed amount of waste produced by plant p in period t (kg)
B^{SP}	Discount breakpoint used for the lot-size transferred from separation centers to the plants (kg)
C_{ct}^{col}	Collection cost in city c in period t (USD/kg)
C_{dt}^{e}	Penalty cost for CO_2 emission from transportation exceeding the emission limit by DC d in period t (USD/kg CO_2)
C_{lt}^{e}	Penalty cost for CH_4 emission from landfilling exceeding the emission limit by landfill l in period t (USD/kg CH_4)
C_{lt}^{land}	Landfilling cost in landfill l in period t (USD/kg)
C_{ndt}^{in}	Inventory cost of product n in DC d in period t (USD/kg)
C_{npct}^{dist}	Cost of electricity n^{el} and heat n^h distribution from WtE plant p to city c in period t (USD/MWh)
C_{npct}^{lost}	Shortage cost of product n in plant p demanded by city c in period t (USD/MWh)
C_{npdt}^{back}	Back-ordering cost of product n in plant p ordered by DC d in period t (USD/kg)
C_{npdt}^{lost}	Shortage cost of product n in plant p demanded by DC d in period t (USD/ kg)
C_{npt}^{in}	Inventory cost of product n in plant p in period t (USD/kg)
C_{npt}^{prod}	Production cost of product n in plant p in period t (USD/kg) or (USD/MWh)

C_{pt}^{e}	Penalty cost for CO_2 emission from transportation exceeding the emission limit by plant p in period t (USD/kg CO_2)
C_{pt}^{oper}	Penalty cost for CO_2 emission from plant operations exceeding the emission limit by plant p in period t (USD/kg CO_2)
C_{pt}^{w}	Penalty cost for waste production exceeding the waste limit by plant p in period t (USD/kg)
C_{st}^{e}	Penalty cost for CO_2 emission from transportation exceeding the emission limit by separation center s in period t (USD/kg CO_2)
C_{wpt}^{in}	Inventory cost of waste w in plant p in period t (USD/kg)
C_{wst}^{in}	Inventory cost of waste w in separation center s in period t (USD/kg)
C_{wst}^{sep}	Separation cost of waste w in separation center s in period t (USD/kg)
C_{v}^{dis}	Distance-dependent transportation cost of vehicle type v (USD/km)
C_{v}^{fix}	Fixed transportation cost of vehicle type v (USD/vehicle)
C_{v}^{time}	Travel time dependent transportation cost of vehicle type v (USD/h)
D_{cs}^{CS}	Distance from collection center c to separation center s (km)
D_{dc}^{DC}	Distance from DC d to city c (km)
D_{ndct}	Demand of product n ordered by city c to DC d in period t (kg)
D_{ndt}	Demand of product n ordered to DC d in period t (kg)
D_{npct}	Demand of product n ordered by city c to plant p in period t (MWh)
D_{npdt}	Demand of product n ordered by DC d to plant p in period t (kg)
$D_{p\tilde{p}}^{PP}$	Distance from plant p to other plant $\tilde{p}$ (km)
D_{pd}^{PD}	Distance from plant p to DC d (km)
D_{pl}^{PL}	Distance from plant p to landfill l (km)
D_{sl}^{SL}	Distance from separation center s to landfill l (km)
D_{sp}^{SP}	Distance from separation center s to plant p (km)
E^{CH_4}	Estimated CH_4 emission from landfilling (kg CH_4 emission/kg of waste)
$E_{v}^{CO_2}$	Estimated CO_2 emission for vehicle type v (kg CO_2 emission/l of fuel)
$E_{wjp}^{CO_2}$	Estimated CO_2 emission from waste w processed by technology j or $\tilde{j}$ in plant p (kg CO_2 emission/kg of waste)
F_{v}	Fuel consumption by vehicle v (l of fuel/km)
L_{lt}	Capacity limit of landfill l in period t
$L_{np\tilde{j}}^{low}$	Lower capacity limit of technology $\tilde{j}$ to process intermediate product n to produce final and energy products in WtE plant p (kg or m^3 or MJ)
$L_{np\tilde{j}}^{up}$	Upper capacity limit of technology $\tilde{j}$ to process intermediate product n to produce final and energy products in WtE plant p (kg or m^3 or MJ)
L_{wpj}^{low}	Lower capacity limit of technology j to process waste w in plant p (kg)
L_{wpj}^{up}	Upper capacity limit of technology j to process waste w in plant p (kg)
L_{v}	Capacity limit of vehicle type v (kg)
P_{nct}	Selling price of product n in city c in period t (USD/kg) or (USD/MWh)
P_{ndt}	Selling price of product n in DC d in period t (USD/kg)
S_{nd}	Storage capacity for product n in DC d (kg)
S_{np}	Storage capacity for product n in plant p (kg)
S_{wp}	Storage capacity for waste w in plant p (kg)
S_{ws}^{nr}	Storage capacity for non-recyclable waste w in separation center s (kg)
S_{ws}^{r}	Storage capacity for recyclable waste w in separation center s (kg)
T_{v}	Travel speed of vehicle type v (km/h)
U_{nd}	Initial inventory level of product n in DC d (kg)
U_{np}	Initial inventory level of product n in plant p (kg)
U_{wp}	Initial inventory level of waste w in plant p (kg)
U_{ws}^{nr}	Initial inventory level of non-recyclable waste w in separation center s (kg)
U_{ws}^{r}	Initial inventory level of recyclable waste w in separation center s (kg)
W_{np}	Amount of waste produced during production of product n in plant p (kg)
W_{wct}	Amount of waste w produced in city c in period t (kg)
α_{wst}^{r}	Percentage of recyclable waste w in separation center s in period t (%)
α_{wst}^{sep}	Separation factor for waste w in separation center s in period t (%)
$\beta_{wn^{r}pj}$	Conversion factor of waste w to recycled product n^{r} by technology j in plant p (kg/kg)

$\gamma_{wn^{int}pj}$	Conversion factor of waste w to intermediate product n^{int} by technology j in plant p (kg/kg or m^3/kg or MJ/kg)
ε_{ndt}	Safety stock coefficient respect to product n in DC d in period t
ε_{npt}	Safety stock coefficient respect to product n in plant p in period t
$\theta_{n^{int}n^{f}p\tilde{j}}$	Conversion factor of intermediate product n^{int} to final product n^{f} by technology $\tilde{j}$in plant p (kg/kg)
ρ_{wpt}	Deterioration rate of waste w in plant p in period t (%)
ρ^{nr}_{wst}	Deterioration rate of non-recyclable waste w in separation center s in period t (%)
ρ^{r}_{wst}	Deterioration rate of recyclable waste w in separation center s in period t (%)
$\tau_{n^{int}n^{h}p\tilde{j}}$	Conversion factor of intermediate product n^{int} to heat n^{h} by technology $\tilde{j}$ in plant p (MJ/m^3 or MJ/MJ)
$\tau_{n^{int}n^{el}p\tilde{j}}$	Conversion factor of intermediate product n^{int} to electricity n^{el} by technology $\tilde{j}$ in plant p (MJ/m^3 or MJ/MJ)
$\varphi_{n^{int}n^{h}p\tilde{j}}$	Conversion efficiency of intermediate product n^{int} to heat n^{h} by technology $\tilde{j}$ in plant p (%)
$\varphi_{n^{int}n^{el}p\tilde{j}}$	Conversion efficiency of intermediate product n^{int} to electricity n^{el} by technology $\tilde{j}$ in plant p (%)
$\chi_{nn^{h}p}$	Amount of intermediate product n required in production heat n^{h} in WtE plant p (m^3/MJ or MJ/MJ)
$\chi_{nn^{el}p}$	Amount of intermediate product n required in production electricity n^{el} in WtE plant p (m^3/MJ or MJ/MJ)
$\chi_{nn^{f}p}$	Amount of intermediate product n required in production final product n^{f} in WtE plant p (kg/kg)
χ_{wnp}	Amount of waste w required in production of a unit of product n in plant p (kg/kg or kg/M^3 or kg/MJ)
$\psi_{n^{int}n^{f}p\tilde{j}t}$	Percentage of conversion of intermediate product n^{int} to final product n^{f} by technology $\tilde{j}$ in plant p in period t (%)
ω	Discount coefficient

Positive variables:

$\tilde{q}_{n^{h}pt}$	Quantity of heat n^{h} that is planned to be produced in plant p in period t (MWh)
$\tilde{q}_{n^{el}pt}$	Quantity of electricity n^{el} that is planned to be produced in plant p in period t (MWh)
$\tilde{q}_{n^{f}pt}$	Quantity of final product n^{f} that is planned to be produced in plant p in period t (kg)
$\tilde{q}_{npt}$	Quantity of product n that is planned to be produced in plant p in period t (kg or m^3 or MJ or MWh)
b_{ndct}	Back-ordered amount of product n in DC d ordered by city c in period t (kg)
b_{npdt}	Back-ordered amount of product n in plant p ordered by DC d in period t (kg)
e^{exc}_{dt}	Amount of CO_2 emission from transportation exceeding the pre-determined limit incurred by DC d in period t (kg CO_2)
e^{exc}_{lt}	Amount of CH_4 emission from landfilling exceeding the pre-determined limit incurred by landfill l in period t (kg CH_4)
e^{exc}_{pt}	Amount of CO_2 emission from transportation exceeding the pre-determined limit incurred by plant p in period t (kg CO_2)
e^{oper}_{pt}	Amount of CO_2 emission from operations exceeding the pre-determined limit incurred by plant p in period t (kg CO_2)
e^{exc}_{st}	Amount of CO_2 emission from transportation exceeding the pre-determined limit incurred by separation center s in period t (kg CO_2)
i_{ndt}	Inventory level of product n in DC d in period t (kg)
i_{npt}	Inventory level of product n in plant p in period t (kg)
i_{wpt}	Inventory level of waste w stored in plant p in period t (kg)
i^{nr}_{wst}	Inventory level of non-recyclable waste w stored in separation center s in period t (kg)
i^{r}_{wst}	Inventory level of recyclable waste w stored in separation center s in period t (kg)
l_{npct}	Lost amount of product n in plant p ordered by city c in period t (MWh)
l_{npdt}	Lost amount of product n in plant p ordered by DC d in period t (kg)
$q_{n^{int}p\tilde{j}t}$	Quantity of intermediate productn^{int}transferred to technology $\tilde{j}$in plant p in period t (kg or MJ or m^3)
q_{lt}	Total quantity of waste received by landfill l in period t (kg)
q_{nct}	Total quantity of product n sold to city c in period t (kg or MWh)
q_{ndcvt}	Quantity of product n transferred from DC d to city c by vehicle v in period t (kg)
q_{ndt}	Total quantity of product n in DC d in period t (kg)
$q_{np\tilde{j}t}$	Quantity of product n transferred to technology $\tilde{j}$in plant p in period t (kg or MJ or m^3)

q_{npct}	Quantity of product n transferred from plant p to city c in period t (MWh)
q_{npdvt}	Quantity of product n transferred from plant p to DC d by vehicle v in period t (kg)
q_{npt}	Quantity of product n produced in plant p in period t (kg or MWh)
q_{plvt}	Quantity of waste transferred from plant p to landfill l by vehicle v in period t (kg)
q_{slvt}	Quantity of waste distributed from separation center s to landfill l by vehicle v in period t (kg)
q_{wcsvt}	Quantity of waste w distributed from city c to separation center s via vehicle type v in period t (kg)
q_{wpjt}	Quantity of waste w transferred to technology j in plant p in period t (kg)
q_{wpt}	Total quantity of waste w transferred to plant p in period t (kg)
q_{wspvt}	Quantity of waste w distributed from separation center s to plant p by vehicle v in period t (kg)
q_{wst}^{in}	Total quantity of waste w transferred to separation center s in period t (kg)
q_{wst}^{nr}	Quantity of non-recyclable waste w inlet to separation center s in period t (kg)
q_{wst}^{r}	Quantity of recyclable waste w inlet to separation center s in period t (kg)
q_{wst}^{sep}	Quantity of separated waste w inlet to separation center s in period t (kg)
r_{ndt}	Required amount of product n demanded by DC d in period t (kg)
$r_{w\tilde{p}pvt}$	Required amount of waste w ordered by plant p to other plant $\tilde{p}$ sent by vehicle v in period t (kg)
r_{wpt}	Required amount of waste w ordered by plant p in period t (kg)
w_{pt}^{exc}	Amount of waste from production process exceeding the pre-determined limit by plant p in period t (kg)

Integer variables

y_{csvt}	Number of vehicle type v required for transportation of waste from collection center c to separation center s in period t
y_{dcvt}	Number of vehicle type v required for transportation of waste from DC d to city c in period t
$y_{p\tilde{p}vt}$	Number of vehicle type v required for transportation of waste from plant p to plant $\tilde{p}$ to in period t
y_{pdvt}	Number of vehicle type v required for transportation of waste from plant p to DC d to in period t
y_{plvt}	Number of vehicle type v required for transportation of waste from plant p to landfill l to in period t
y_{slvt}	Number of vehicle type v required for transportation of waste from separation center s to landfill l in period t
y_{spvt}	Number of vehicle type v required for transportation of waste from separation center s to plant p in period t

Binary variables

$z_{np\tilde{j}t}^{send}$	Equals one when product n in plant p is sent to technology $\tilde{j}$ in period t; otherwise zero
z_{wpjt}^{send}	Equals one when waste w in plant p is sent to technology j in period t; otherwise zero

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