Optimal Planning for the Reuse of Municipal Solid Waste Considering Economic, Environmental, and Safety Objectives

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A mathematical programming model is presente for the optimal planning of the reuse of municipal solid waste (MSW) to maximize the economic benefit while simultaneously considering sustainability and safety criteria. The proposed methodology considers several phases of the supply chain including waste separation, distribution to processing facilities, processing to obtain useful products, and distribution of products to consumers. Additionally, the safety criteria are based on the potential fatalities associated with waste management. The proposed optimization model is formulated as a multiobjective optimization problem, which considers three different objectives including the maximization of the net annual profit, the maximization of the amount of reused MSW, and the minimization of the social risk associated with the supply chain. The proposed model is applied to a case study in the central-west region of Mexico. The results show the tradeoff between the social risk and the economic and environmental criteria. © 2015 American Institute of Chemical Engineers *AIChE J*, 61: 1881–1899, 2015
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Introduction

Nowadays, municipal solid waste (MSW) management is an important practice that addresses critical societal needs. The enormous generation of MSW is directly related to the current human lifestyle. Over the past decade, MSW disposal has increased drastically from 0.5 kg/(person day) to 1.7 kg/(person day).[1] This has represented a serious problem particularly for countries where effective strategies for MSW management are not well established.[2] Inappropriate waste disposal may lead to serious side effects including groundwater pollution, health risks, and serious safety issues such as fire and explosion that may lead to fatalities.[3] As such, a sustainable and efficient waste management strategy is needed to balance the need for the development of the quality of human life and the protection of the environment.[4] For the optimal planning of MSW management, it is necessary to consider the entire supply chain of the system including tasks like MSW recollection, transportation, treatment, production of value added products, and distribution of products.[5] In this context, Varbanov et al.[6] introduced a new indicator, called waste energy potential utilization, to measure the impact of logistics and energy distribution from MSW. Hokkanen and Salminen[7] reported a methodology to take into account several criteria for the selection of a MSW management system. Hung et al.[8] presented a review of models to support the decision making in MSW management. In addition, a classification for the models utilized in the area of MSW management was reported by Morrisey and Brown[9] and Karmperis et al.[10] Santibañez-Aguilar et al.[11] proposed a mathematical programming model for the optimal planning of a supply chain for MSW management considering economic and environmental aspects. Also, Tan et al.[4] reported an optimization model for synthesizing MSW processing networks to produce energy and value-added products achieving economic and environmental issues. Bowling et al.[12] developed an approach to determine optimal locations and sizes of biomass-management facilities. Furthermore, Minoglou and Komilis[13] presented a simplified methodology to optimize an integrated MSW management

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system considering the minimization of the total annual cost and the equivalent carbon dioxide emissions. Additionally, Capón-García et al.[14] presented a multiperiod and multiobjective optimization formulation for MSW management considering economic and environmental issues, where treatment was modeled as a black-box model. Ng et al.[15] reported an approach for synthesizing waste-to-energy networks using MSW. Onel et al.[16] presented a mathematical programming model for yielding MSW to liquid transportation networks, and then Niziolek et al.[17] incorporated a global optimization approach for solving this problem.

Although the economic and environmental issues are certainly critical in the management of MSW, the social aspects have been overlooked or considered as an afterthought following the design. Specifically, for the case of supply chains focused on biomass conversion, You et al.[18] addressed the optimal design and planning of cellulosic ethanol supply chains under economic, environmental, and social objectives and Santibañez-Aguilar et al.[19] proposed a three-objective optimization formulation for the optimal planning of supply chains involving economic, environmental, and social objectives, where the social objective was measured through the number of generated jobs. Conversely, for MSW management systems, Galan et al.[20] introduced the consideration of economic, environmental, and social aspects in the design of a new MSW management network in the north of Spain. An additional way to consider the social aspect is through the risk assessment. In this regard, Sugiyama et al.[21] presented a novel framework of chemical process design including four stages of decision making considering economy, life-cycle environmental impacts, people health, and safety aspects. Additionally, a structured methodology for risk identification for chemical plants was presented by Adhitya et al.[22] Moreover, Ng et al.[23] presented a systematic approach for the synthesis and optimization of a sustainable integrated biorefinery that considers economic, environmental, inherent safety, and inherent occupational health performances. Besides, Bernechea and Arnaldos[24] proposed a methodology to minimize the risk associated with a storage facility applying quantitative risk assessment to create a risk objective function; however, the risk assessment has not been considered simultaneously in the design phase of the supply chain. Fabiano et al.[25]presented a site-oriented framework for risk assessment and developed a theoretical approach for emergency planning and optimization. Furthermore, El-Halwagi et al.[26] proposed a new approach to simultaneously take into account safety and economic factors for the optimal planning of supply chains of biorefineries. Also, van Raemdonck et al.[27] carried out a study about risk analysis for the transportation of hazardous materials and introduced a methodology to calculate a local accidental risk. For the specific case of MSW, Das et al.[28] proposed a risk assessment framework for the transportation of inflammable hazardous waste. In addition, Dadashzadeh et al.[29] presented a risk-based approach for analyzing the exposure to a hazardous material. Vadenbo et al.[30] reported a multiobjective optimization approach waste management in industrial networks.

The societal risk is a very important issue associated with the MSW supply chain. One of the main risks associated with the supply chain for the MSW is leaching of pollutants through the dissolution of soluble matters from the solid phase into a liquid phase (e.g., water). The characteristics of the leachate depend on the composition of the waste and water content because the leachate composition is the result of a reaction between various mineral phases in the waste and the leaching fluid. Leaching becomes an important risk when people live around the landfills or dumps and drink water from shallow wells. In this context, pollutants are filtered through the land for an undefined period, causing serious health damages on population. Another important risk associated with the MSW management is the gas emission due to accidents and burning of the stored waste in the landfill. For this risk, it is necessary to consider the combustion rate, because in most of the cases the fire is uncontrolled and the amount of burned trash as well as the time of the fire should be considered. In addition, this risk mainly depends on the concentration of pollutants, distribution and distance between emissary and receptor, and the type of the emitted pollutant, because carcinogenic and noncarcinogenic substances affect people in different ways.

It should be noticed that none of the aforementioned methodologies for the optimization of the MSW management system has simultaneously considered the societal risk associated with the system together with the economic, environmental, and social concerns. Particularly, safety is an issue of paramount importance in the MSW supply chain that must be considered to provide sustainable processes.

Therefore, based on the model formulation by Santibañez et al.,[11] where only economic and environmental aspects were considered, this article presents a mathematical programming model for the optimal planning of the reuse of MSW to include safety issues. The economic issue takes into account the maximization of the net annual profit of the waste management system, whereas the environmental objective considers the maximization of the reused waste. The major contribution of this article is to include the societal risk or the safety aspect, which is very important in the supply chain associated to the MSW management system, and can be used to balance the other two objectives. This way, if only the economic and environmental criteria were taken into account, the optimal location of the landfills would be placed near to highly populated zones, which drastically increases the societal risk. Moreover, the current work considers two of the main aspects of the societal risk for the waste management system such as the leaching of pollutants through the water table and the gas emissions due to accidents and burning of the stored waste in the landfills. It is worth noting that a gas dispersion model has to be considered to obtain the concentration that may affect the population located near to the landfill. In addition, the models to obtain the societal risk through the toxicity of the gaseous pollutants and leaching have nonconvex terms, which depend on a large number of variables and the solution may be too complex. For this reason, in this article there are proposed models to assess the societal risk, which have been reformulated to obtain a simple mathematical model that can be easily implemented in the optimization formulation for the supply chain associated to the MSW management. The optimization model is capable of selecting the processing technologies, consumers, waste treated from different cities, recycled waste, products, and location of processing facilities.

Problem Statement

The addressed problem considers several cities for the implementation of a waste management system. Each city is divided in several sections denominated sites. Here, it is

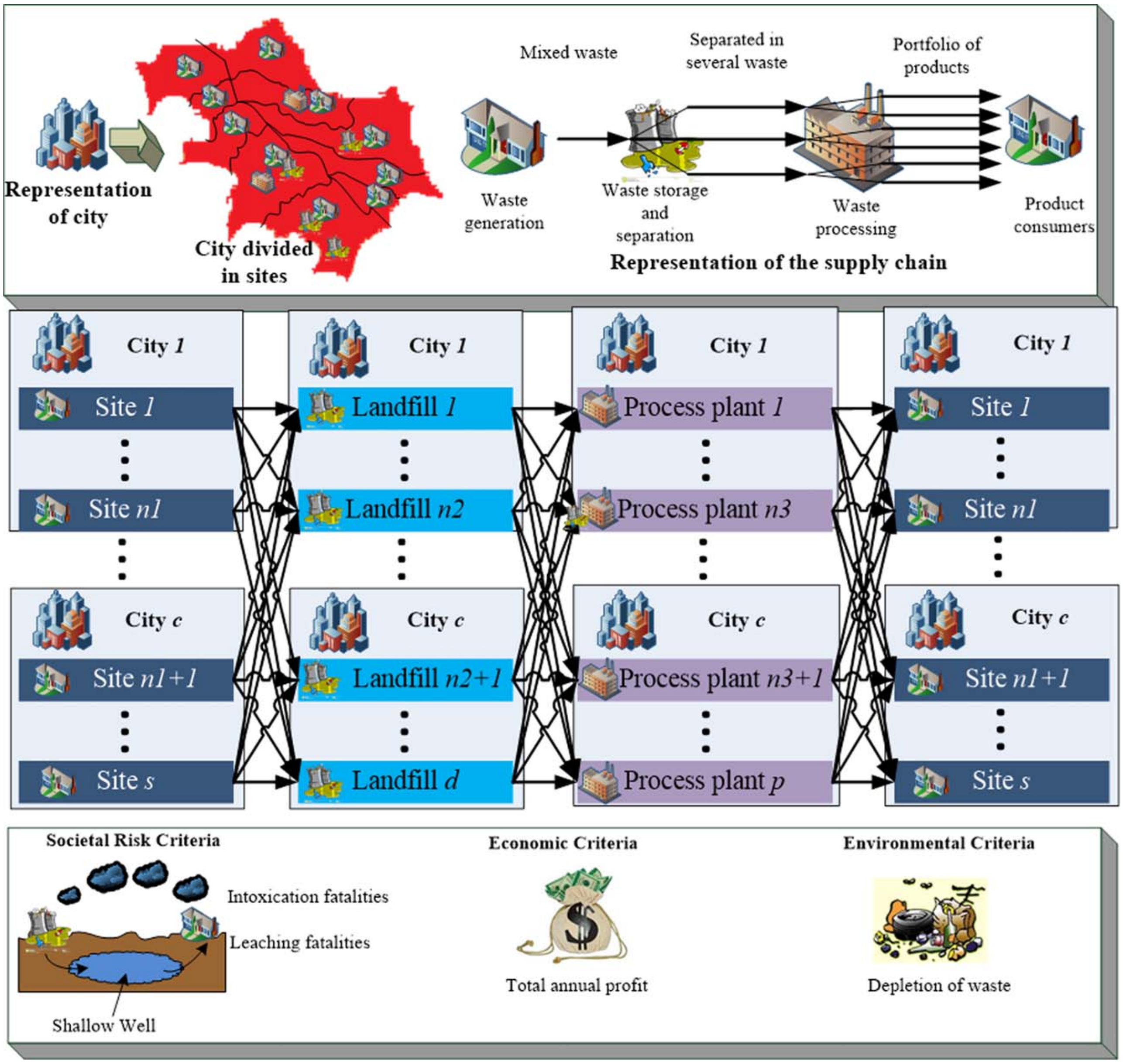

Figure 1. Proposed superstructure for optimizing the MSW management system considering the risk assessment.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

important to mention that each site has associated different parameters such as population density, waste production per capita, product demand, price of products, etc. Also, the current approach considers several disposal centers denominated dumps. This way, the dumps or landfills are the places where the waste is stored, in the dumps the waste is separated to be sent to the processing facilities. The processing facilities receive the separated waste to yield useful products such as energy, recycled materials, olefins, fuels, etc. Each processing facility has a given production capacity, different conversion technologies to process the waste and storage limits. It is worth mentioning that the dumps and the processing plants are allocated in different sites. Finally, the products are distributed from the processing plants to the final consumers. In this case, the final consumers are the sites located in the cities.

Additionally, the mathematical model considers two of the main significant risks for the population for the implementation of a waste management system. On the one hand, the consumption of polluted water since the pollutants in dumps may be transported through leaching from the surface to shallow wells that can serve as water source to the population. On the other hand, it is considered the intoxication by gas emissions caused by burning in a given dump and dispersed into the atmosphere. This way, other locations are taken into account, which correspond to the affected points by the gas emissions, since the gas emissions from a dump can affect a specific area near to the dump; in other words, it is difficult that the gas emissions affect all the surface of the site where the dump is located as well as another site or another city.

Figure 1 shows the proposed superstructure for solving the addressed problem, which is the basis for the optimization formulation presented in next section.

Model Formulation

The indexes used in the optimization formulation are first defined. These indexes are used to define materials, locations, processing routes, pollutants, and intervals. For the case of materials, the index *wn* represents the considered waste in the supply chain and *p* is utilized for products. Also, there are several considered locations, in this way, the sites are represented through the index *s*, the processing plants are defined by the index *pk*, the landfills are given by the index *d*, and the affected sites by the gas emissions are given by the index *a*. Furthermore, the index *g* represents the pollutant in the gas emissions for burning of dumps and the pollutants in the leaching are given by the index *k*. Conversely, the processing routes for the waste are defined through the index *r* and finally, the indexes $z_{d,a}$, *j*, and $y_{d,a}$ represent the different intervals used for the disjunctions. Then the model formulation is presented as follows.

Waste transportation from sites in cities to dumps

The sites in each city produce different MSW ($W^{\text{produced}}_{wn,s}$) and this is distributed to the different dumps ($W^{\overset{\text{distributed}}{\text{dump}}}_{wn,s,d}$); in addition, the waste at the inlet of the dumps ($W^{\overset{\text{in}}{\text{dump}}}_{wn,d}$) is the sum of the distributed waste from sites to dumps ($W^{\overset{\text{distributed}}{\text{dump}}}_{wn,s,d}$)

$$W^{\text{produced}}_{wn,s} = \sum_{d \in \text{DUMPS}} W^{\overset{\text{distributed}}{\text{dump}}}_{wn,s,d}, \quad \forall wn \in \text{WASTE}, s \in \text{SITES} \tag{1}$$

$$W^{\overset{\text{n}}{\text{dump}}}_{wn,d} = \sum_{s \in \text{SITES}} W^{\overset{\text{distributed}}{\text{dump}}}_{wn,s,d}, \quad \forall wn \in \text{WASTE}, d \in \text{DUMPS} \tag{2}$$

Waste balances in dumps

The MSW stored in dumps ($W^{\text{total}}_{wn,d}$) is equal to the MSW inlet to the dump ($W^{\overset{\text{in}}{\text{dump}}}_{wn,d}$) minus the MSW outlet from the dump ($W^{\overset{\text{out}}{\text{dump}}}_{wn,d}$). The outlet MSW ($W^{\overset{\text{out}}{\text{dump}}}_{wn,d}$) is limited by the maximum possible percentage of waste separation. In this context, each site *s* has several dumps *d* to store MSW and the amount of available waste ($\alpha^{\overset{\text{separation}}{\text{factor}}}_{wn,d} W^{\text{total}}_{wn,d}$) should be greater than the used waste ($W^{\overset{\text{out}}{\text{dump}}}_{wn,d}$) to produce the considered products, where the available waste is equal to a separation factor ($\alpha^{\overset{\text{separation}}{\text{factor}}}_{wn,d}$) multiplied by the total stored waste in the dump *d* ($W^{\text{total}}_{wn,s,d}$)

$$W^{\text{total}}_{wn,d} = W^{\overset{\text{in}}{\text{dump}}}_{wn,d} - W^{\overset{\text{out}}{\text{dump}}}_{wn,d}, \quad \forall wn \in \text{WASTE}, d \in \text{DUMPS} \tag{3}$$

$$W^{\overset{\text{out}}{\text{dump}}}_{wn,d} \leq \alpha^{\overset{\text{separation}}{\text{factor}}}_{wn,d} W^{\text{total}}_{wn,d}, \quad \forall wn \in \text{WASTE}, d \in \text{DUMPS} \tag{4}$$

Waste distribution from dumps to processing plants

To consider the distribution of waste from dumps to processing plants, it is necessary to remark that there are several processing plants in each city; then, a different index for processing plants is considered, in this case, the transportation is taken into account from dump *d* to processing facility *pk*. In this way, the transported waste from each dump ($W^{\overset{\text{out}}{\text{dump}}}_{wn,d}$) is equal to the sum of the distributed waste in each processing facility ($W^{\overset{\text{distributed}}{\text{plant}}}_{wn,d,pk}$)

$$W^{\overset{\text{out}}{\text{dump}}}_{wn,d} = \sum_{pk \in \text{FACILITIES}} W^{\overset{\text{distibuted}}{\text{plant}}}_{wn,d,pk}, \quad \forall wn \in \text{WASTE}, d \in \text{DUMPS} \tag{5}$$

Also, the waste in each processing plant ($W^{\overset{\text{in}}{\text{plant}}}_{wn,pk}$) must be equal to the sum of the transported waste from each dump ($W^{\overset{\text{distributed}}{\text{plant}}}_{wn,d,pk}$)

$$W^{\overset{\text{in}}{\text{plant}}}_{wn,pk} = \sum_{d \in \text{DUMPS}} W^{\overset{\text{distributed}}{\text{plant}}}_{wn,d,pk}, \quad \forall wn \in \text{WASTE}, pk \in \text{FACILITIES} \tag{6}$$

Furthermore, there is required the inclusion of upper and lower limits for transportation from dumps to processing facilities

$$W^{\overset{\text{distributed}}{\text{plant}}}_{wn,d,pk} \leq \text{upp}W^{\overset{\text{distributed}}{\text{plant}}}_{\text{wn,d,pk}}, \quad \forall wn \in \text{WASTE}, d \in \text{DUMPS}, pk \in \text{FACILITIES} \tag{7}$$

$$W^{\overset{\text{distributed}}{\text{plant}}}_{wn,d,pk} \geq \text{low}W^{\overset{\text{distributed}}{\text{plant}}}_{\text{wn,d,pk}}, \quad \forall wn \in \text{WASTE}, d \in \text{DUMPS}, pk \in \text{FACILITIES} \tag{8}$$

MSW processing

The MSW is processed to obtain value-added products. In this way, the waste in plant ($W^{\overset{\text{in}}{\text{plant}}}_{wn,pk}$) is distributed to various processing routes ($W^{\overset{\text{distributed}}{\text{routes}}}_{wn,pk,r}$) to obtain products using a conversion factor ($\alpha^{\text{conversion}}_{wn,p,r}$) as follows

$$W^{\overset{\text{in}}{\text{plant}}}_{wn,pk} = \sum_{r \in \text{ROUTES}} W^{\overset{\text{distributed}}{\text{routes}}}_{wn,pk,r}, \quad \forall wn \in \text{WASTE}, pk \in \text{FACILITIES} \tag{9}$$

$$P^{\overset{\text{processing}}{\text{plant}}}_{p,pk} = \sum_{r \in \text{ROUTES}} \sum_{wn \in \text{WASTE}} \alpha^{\text{conversion}}_{wn,p,r} W^{\overset{\text{distributed}}{\text{routes}}}_{wn,pk,r}, \quad \forall p \in \text{PRODUCTS}, pk \in \text{FACILITIES} \tag{10}$$

Distribution of products from processing facilities to consumers

Products can be distributed from processing plants to consumers; these consumers are located in the cities. This way, the products in processing plants ($P^{\overset{\text{processing}}{\text{plant}}}_{p,pk}$) can be distributed to the consumers ($P^{\overset{\text{distributed}}{\text{product}}}_{p,pk,s}$) as follows

$$P^{\overset{\text{processing}}{\text{plant}}}_{p,pk} = \sum_{s \in \text{SITES}} P^{\overset{\text{distributed}}{\text{product}}}_{p,pk,s}, \quad \forall p \in \text{PRODUCTS}, pk \in \text{FACILITIES} \tag{11}$$

And the sum of distributed products ($P^{\overset{\text{distributed}}{\text{product}}}_{p,pk,s}$) is equal to the products for a given consumer ($P^{\overset{\text{product}}{\text{consumer}}}_{p,s}$)

$$P^{\overset{\text{product}}{\text{consumer}}}_{p,s} = \sum_{pk \in \text{FACILITIES}} P^{\overset{\text{distributed}}{\text{product}}}_{p,pk,s}, \quad \forall p \in \text{PRODUCTS}, s \in \text{SITES} \tag{12}$$

Demand of products in cities

Each site has a specific demand for each product ($\text{PD}^{\overset{\text{product}}{\text{consumer}}}_{p,s}$), which must be greater than the products sent to consumers ($P^{\overset{\text{product}}{\text{consumer}}}_{p,s}$) from the recycled MSW

$$P_{p,s}^{\substack{\text{product}\\\text{consumer}}} \leq \text{PD}_{p,s}^{\substack{\text{product}\\\text{consumer}}} \quad \forall p \in \text{PRODUCTS}, s \in \text{SITES} \tag{13}$$

Revenue from sales

The revenue from selling products (REVENUE) is the sum of the unitary product cost ($C_p^{\substack{\text{unitary}\\\text{product}}}$) multiplied by the total consumed product ($P_{p,s}^{\substack{\text{product}\\\text{consumer}}}$)

$$\text{REVENUE} = \sum_{p \in \text{PRODUCTS}} \sum_{s \in \text{SITES}} C_p^{\substack{\text{unitary}\\\text{product}}} P_{p,s}^{\substack{\text{product}\\\text{consumer}}} \tag{14}$$

Operating costs

The operating cost for processing facilities (OPCOST) is obtained multiplying the unitary processing cost for each processing technology in each processing plant ($C_{wn,p,pk,r}^{\substack{\text{unitary}\\\text{processing}}}$) times the amount of MSW that is processed in the processing facility for the given processing route ($W_{wn,pk,r}^{\substack{\text{distributed}\\\text{routes}}}$)

$$\text{OPCOST} = \sum_{wn \in \text{WASTE}} \sum_{p \in \text{PRODUCTS}} \sum_{pk \in \text{FACILITIES}} \sum_{r \in \text{ROUTES}} C_{wn,p,pk,r}^{\substack{\text{unitary}\\\text{processing}}} W_{wn,pk,r}^{\substack{\text{distributed}\\\text{routes}}} \tag{15}$$

Capital cost

The capital cost for the processing technologies usually has a nonlinear behavior with respect to the amount of processed waste; however, this dependence can be linearized through a disjunctive mathematical programing formulation, this linearization is similar to the one used for risk assessment. The disjunction considers that if the processed waste is between given limits, the binary variable associated with the disjunction is activated and so the corresponding cost

$$\vee_q \begin{bmatrix} Y_{wn,pk,r,q}^{\text{economies}} \\ W_{wn,pk,r}^{\substack{\text{distributed}\\\text{routes}}} \geq \text{low}W_{wn,pk,r,q}^{\substack{\text{distributed}\\\text{routes}}} \\ W_{wn,pk,r}^{\substack{\text{distributed}\\\text{routes}}} \leq \text{upp}W_{wn,pk,r,q}^{\substack{\text{distributed}\\\text{routes}}} \\ \text{CAPCOST}_{wn,pk,r}^{\text{economies}} = B_{wn,pk,r,q}^{\substack{\text{cap}\\\text{economies}}} W_{wn,pk,r}^{\substack{\text{distributed}\\\text{routes}}} + A_{wn,pk,r,q}^{\substack{\text{cap}\\\text{economies}}} \end{bmatrix}, \quad \begin{matrix} \forall wn \in \text{WASTE}, \\ pk \in \text{FACILITIES}, \\ r \in \text{ROUTES}, \\ q \in \text{ECON} \end{matrix}$$

Previous disjunction is reformulated as follows. First, just one segment can be selected

$$\sum_{q \in \text{ECON}} y_{wn,pk,r,q}^{\text{economies}} = 1, \forall wn \in \text{WASTE}, pk \in \text{FACILITIES}, r \in \text{ROUTES} \tag{16}$$

Then, the continuous variables are disaggregated for each segment

$$W_{wn,pk,r}^{\substack{\text{distributed}\\\text{routes}}} = \sum_{q \in \text{ECON}} Wd_{wn,pk,r,q}^{\substack{\text{distributed}\\\text{routes}}}, \forall wn \in \text{WASTE}, pk \in \text{FACILITIES}, r \in \text{ROUTES} \tag{17}$$

$$\text{CAPCOST}_{wn,pk,r}^{\text{economies}} = \sum_{q \in \text{ECON}} d\text{CAPCOST}_{wn,pk,r,q}^{\text{economies}}, \quad \forall wn \in \text{WASTE}, pk \in \text{FACILITIES}, r \in \text{ROUTES} \tag{18}$$

$$\text{CAPCOST}^{\text{total}} = K_{\text{F}} \cdot \sum_{wn \in \text{WASTES}} \sum_{pk \in \text{FACILITIES}} \sum_{r \in \text{ROUTES}} \text{CAPCOST}_{wn,pk,r}^{\text{economies}} \tag{19}$$

Finally, the constraints are stated in terms of the disaggregated variables

$$Wd_{wn,pk,r,q}^{\substack{\text{distributed}\\\text{routes}}} \geq \text{low}W_{wn,pk,r,q}^{\substack{\text{distributed}\\\text{routes}}} y_{wn,pk,r,q}^{\text{economies}}, \forall wn \in \text{WASTE}, pk \in \text{FACILITIES}, r \in \text{ROUTES}, q \in \text{ECON} \tag{20}$$

$$Wd_{wn,pk,r,q}^{\substack{\text{distributed}\\\text{routes}}} \leq \text{upp}W_{wn,pk,r,q}^{\substack{\text{distributed}\\\text{routes}}} y_{wn,pk,r,q}^{\text{economies}}, \forall wn \in \text{WASTE}, pk \in \text{FACILITIES}, r \in \text{ROUTES}, q \in \text{ECON} \tag{21}$$

$$d\text{CAPCOST}_{wn,pk,r}^{\text{economies}} = B_{wn,pk,r,q}^{\substack{\text{cap}\\\text{economies}}} Wd_{wn,pk,r,q}^{\substack{\text{distributed}\\\text{routes}}} + A_{wn,pk,r,q}^{\substack{\text{cap}\\\text{economies}}} y_{wn,pk,r,q}^{\text{economies}}, \forall wn \in \text{WASTE}, pk \in \text{FACILITIES}, r \in \text{ROUTES}, q \in \text{ECON} \tag{22}$$

Transportation costs

The transportation cost is an important cost in any supply chain, because this cost depends on the distance between the facilities as well as the transported amount of materials; furthermore, this cost allows determining the amount that should be transported from one place to another. One of the most used ways to model the cost of this activity is given as follows: the transportation cost is equal to the distance between the facilities multiplied by the transported amount of material and multiplied by a unitary transportation cost that depends on the specific material. Equation 23 shows the total transportation cost, which is the sum of the transportation cost of sites-landfills (see Eq. 24), landfills-processing facilities (see Eq. 25), and processing facilities-consumers (see Eq. 26)

$$\text{TRANSPCOST} = \text{TRANSPCOST}^{\substack{\text{SITES}-\\\text{LANDFILLS}}} + \text{TRANSPCOST}^{\substack{\text{LANDFILLS}-\\\text{FACILITIES}}} + \text{TRANSPCOST}^{\substack{\text{FACILITIES}-\\\text{CONSUMERS}}} \tag{23}$$

$$\text{TRANSPCOST}^{\substack{\text{SITES}-\\\text{LANDFILLS}}} = \sum_{wn \in \text{WASTE}} \sum_{d \in \text{DUMPS}} \sum_{s \in \text{SITES}} D1_{s,d}^{\text{transp}} W_{wn,s,d}^{\substack{\text{distributed}\\\text{dump}}} C1_{wn}^{\text{transp}} \tag{24}$$

$$\mathrm{TRANSPCOST}^{\substack{\text{LANDFILLS-}\\ \text{FACILITIES}}} = \sum_{wn\in \mathrm{WASTE}} \sum_{d\in \mathrm{DUMPS}} \sum_{s\in \mathrm{FACILITIES}} D2^{\mathrm{transp}}_{d,pk} W^{\substack{\text{distibuted}\\ \text{plant}}}_{wn,d,pk} C2^{\mathrm{transp}}_{wn} \tag{25}$$

$$\mathrm{TRANSPCOST}^{\substack{\text{FACILITIES-}\\ \text{COSNUMERS}}} = \sum_{p\in \mathrm{PRODUCTS}} \sum_{pk\in \mathrm{FACILITES}} \sum_{s\in \mathrm{SITES}} D3^{\mathrm{transp}}_{s,pk} P^{\substack{\text{distributed}\\ \text{product}}}_{p,pk,s} C3^{\mathrm{transp}}_{p} \tag{26}$$

Disposal cost

The disposal cost considers all activities needed for the disposal of MSW, this cost is given through a linear function, and this cost considers the unused waste. The disposal cost is equal to the unused waste multiplied by a unitary cost for disposal

$$\mathrm{DISPCOST} = \sum_{d\in \mathrm{DUMPS}} \left(C^{\mathrm{disp}}_{d} \sum_{wn\in \mathrm{WASTE}} W^{\mathrm{total}}_{wn,d} \right) \tag{27}$$

Separation cost

Finally, the separation cost takes into account the amount of waste that is separated and distributed to the processing facilities, it is important to note that the separated waste must be processed. This cost is equal to the separated waste multiplied by a unitary separation cost

$$\mathrm{SEPCOST} = \sum_{wn\in \mathrm{WASTE}} \sum_{d\in DUMPS} C^{\mathrm{sep}}_{wn} W^{\substack{\text{out}\\ \text{dump}}}_{wn,d} \tag{28}$$

Economic objective function

The economic objective function is the net annual profit and considers all the costs of the entire supply chain; in this context, the net annual profit is the revenue from sales minus the operating, capital, transportation, disposal, and separation costs. It is important to mention that this objective function is the net profit for the implementation of this type of waste management system, and it is generated from the point of view of the government and the profit for another entity of the supply chain may be different to the one of Eq. 29

$$\begin{aligned}\mathrm{NETPROFIT} = {} & \mathrm{REVENUE} - \mathrm{OPCOST} - \mathrm{CAPCOST}^{\mathrm{total}} \\ & - \mathrm{TRANSPCOST} - \mathrm{DISPCOST} - \mathrm{SEPCOST}\end{aligned} \tag{29}$$

Total consumed waste

The measure for the total consumed waste is a way to take into account the environmental impact. Although there are many other forms to assess the environmental impact, this is an adequate way for the case of the MSW because one of the main impacts is for the huge amount of waste that is disposed in landfills. In this way, the total consumed waste is equal to the total waste that is sent to the processing facilities from dumps divided by the total waste that is produced in each site of the different cities

$$\mathrm{WASTECONS} = \sum_{wn\in \mathrm{WASTE}} \sum_{d\in DUMPS} W^{\substack{\text{out}\\ \text{dump}}}_{wn,d} \Big/ \sum_{wn\in \mathrm{WASTES}} \sum_{s\in \mathrm{SITES}} W^{\mathrm{produced}}_{wn,s} \tag{30}$$

Risk assessment

Risk assessment is based on the application of a societal risk.[31] The toxicity due to exposure to substances derived from leaching and burning dumps was considered for the calculation of societal risk in the entire supply chain. These potential risk are determined as follows:

Risk for leaching

The risk for leaching depends on each shallow well (in each site is considered a shallow well) as well as each dump; in this case, each shallow well is associated with a given population. The societal risk ($F^{\substack{\text{leaching}\\ \text{fatalaties}}}_{k,s}$) is obtained multiplying the exposed population ($P^{\mathrm{population}}_{s}$) times the probability of fatalities ($\alpha^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s}$). It is important to note that one dump can pollute several shallow wells

$$F^{\substack{\text{leaching}\\ \text{fatalaties}}}_{k,s} = \alpha^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s} P^{\mathrm{population}}_{s}, \forall s \in \mathrm{SITES}, k \in \mathrm{POLLUTANT} \tag{31}$$

The probability of fatalities $\alpha^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s}$ is obtained from the dose ($C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,s}$)-response ($\alpha^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s}$) curve associated with a particular pollutant; this way, for each pollutant presents in a shallow well, it is possible to obtain a function for fatalities. The function to obtain the fatalities is nonlinear; however, the function can be limited to a given concentration to consider a linear function. The linearization is modeled with a disjunction to approximate the dose-response curve with several linear equations.

$$\vee_i \begin{bmatrix} Y^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s,i} \\ C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,s} \geq \mathrm{low}\ C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,i} \\ C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,s} \leq \mathrm{upp}\ C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,i} \\ \alpha^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s} = M^{\substack{\text{probit}\\ \text{leaching}}}_{k,i} C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,s} + B^{\substack{\text{probit}\\ \text{leaching}}}_{k,i} \end{bmatrix} \begin{matrix} s \in \mathrm{SITES} \\ , \forall\, k \in \mathrm{POLLUTANT} \\ i \in \mathrm{INTERVALS} \end{matrix}$$

Previous formulation is reformulated through the convex hull technique, where Eqs. 32 and 33 are used to activate the binary variables in each valid interval ($y^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s,i}$), which are 1 when the concentration is between the corresponding lower ($\mathrm{low}C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,i}$) and upper ($\mathrm{upp}C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,i}$) limits

$$Cd^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,s.i} \geq \mathrm{low}C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,i} y^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s,i}, \forall k \in \mathrm{POLLUTANT}, d \in \mathrm{DUMPS}, s \in \mathrm{SITES}, i \in \mathrm{INTERVALS} \tag{32}$$

$$Cd^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,s.i} \leq \mathrm{upp}C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,i} y^{\substack{\text{leaching}\\ \text{fatalities}}}_{k,s,i}, \forall k \in \mathrm{POLLUTANT}, d \in \mathrm{DUMPS}, s \in \mathrm{SITES}, i \in \mathrm{INTERVALS} \tag{33}$$

Also, the number of selected intervals should be equal to 1. This way, the sum of the binary variables with respect to

Table 1. Considered Data to Obtain the Emission Factors for the Gas Dispersion Model[32–36]

Data for the Gas Dispersion Model			
Symbol	Description	Value	Consideration
$z_{d,a}$	Height of receptor	1.63 m	Average height of population
$y_{d,a}$	Perpendicular distance of receptor	0 m	Line segment from emissary to receptor
u	Wind velocity	1.5 m	Defined as the worst case
$H_{r,a}$	Effective height of emissary	0 m	The emission are from the surface of the landfill

Data for the Probit Function for the Pollutant Considered			
Symbol	Description	Value	Pollutant
a	Independent term in Probit function	−13.97	Nitrogen Dioxide
b	Coefficient of the logarithm	1.4	
n	Exponent of the concentration	2	
t	Exposition time	28 800 s	

the intervals has to be equal to 1 to ensure that only one interval is chosen

$$\sum_{i\in \text{INTERVALS}} y_{k,s,i}^{\text{leaching fatalities}} = 1, \forall k \in \text{POLLUTANT}, d \in \text{DUMPS}, s \in \text{SITES} \tag{34}$$

Furthermore, the continuous variables need to be disaggregated, where the total variable is the sum for each interval of the discretized variables

$$C_{k,s}^{\text{phreatic concentration}} = \sum_{i\in \text{INTERVALS}} Cd_{k,s.i}^{\text{phreatic concentration}}, \forall k \in \text{POLLUTANT}, d \in \text{DUMPS}, s \in \text{SITES} \tag{35}$$

$$\alpha_{k,s}^{\text{leaching fatalities}} = \sum_{i\in I\text{NTERVALS}} \alpha d_{k,s,i}^{\text{leaching fatalities}}, \forall k \in \text{POLLUTANT}, d \in \text{DUMPS}, s \in \text{SITES} \tag{36}$$

And finally, the constraints inside the disjunction are stated in terms of the disaggregated variables

$$\alpha d_{k,s,i}^{\text{leaching fatalities}} = M_{k,i}^{\text{probit leaching}} Cd_{k,s.i}^{\text{phreatic concentration}} + B_{k,i}^{\text{probit leaching}} y_{k,s,i}^{\text{leaching fatalities}}, \forall k \in \text{POLLUTANT}, d \in \text{DUMPS}, s \in \text{SITES}, i \in \text{INTERVALS} \tag{37}$$

Also, the pollutant concentration depends on a lot of factors, some of them are the quantity of pollutant in the surface of a dump ($C_{k,d}^{\text{dump quantity}}$) and the level of the water. This is important because the land is a natural filter, which can eliminate some pollutants and can be modeled as a black box model associated with an efficiency factor ($\alpha_{k,d,s}^{\text{filtration factor}}$) that depends on the type of land, water level, type of pollutant between others factors, and this should be obtained experimentally and modeled as follows

$$C_{k,s}^{\text{phreatic concentration}} = \left(\delta_{s\,\text{quantity-concentration}}\right) \sum_{d\in \text{DUMPS}} \alpha_{k,d,s}^{\text{filtration factor}} C_{k,d}^{\text{dump quantity}}, \forall k \in \text{POLLUTANT}, d \in \text{DUMPS}, s \in \text{SITES} \tag{38}$$

In addition, the quantity of pollutants in each dump ($C_{k,d}^{\text{dump quantity}}$) is calculated through a factor ($\beta_{k,d}^{\text{pollutant surface}}$) multiplied by the total amount of waste in each dump

$$C_{k,d}^{\text{dump quantity}} = \beta_{k,d}^{\text{pollutant surface}} \left(\sum_{wn\in \text{WASTE}} W_{wn,d}^{\text{total}}\right), \forall k \in \text{POLLUTANT}, d \in \text{DUMPS} \tag{39}$$

Risk for toxic emissions for burning of dumps

Due to the ambient conditions in the dumps, it is common to consider the fire of hazard substances, therefore, to take into account the societal risk due to exposure to toxic pollutants produced when the dump is burning, it is required to use a dispersion gas model. In this way, the Pasquill Gifford model is an adequate way to consider the dispersion of gases. According with the equation of Pasquill Gifford, the concentration of pollutants for the dispersion of gases ($C_{g,s,d^{\text{toxic concentration}}}$) depends on the emission rate of the source ($Q_{g,d}$) multiplied by a factor that depends on the position of the receptor with respect to the emitter

$$C_{g,d,a}^{\text{toxic concentration}} = Q_{g,d}\alpha_{d,a}^{\text{dispersion}}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS} \tag{40}$$

where the factor $\alpha_{d,a}^{\text{dispersion}}$ depends on the position obtained from the Pasquill Gifford equation.[32] The position is taken

Table 2. Data of Waste Generation and Population for Each Site of Each City[36]

			Waste Production												
		Population (People)	PP	PE	PET	PS	HDPE	Aluminium	Clear Glass	Green Glass	Brown Glass	Paper	Non-reciclables	Surface	Population Density
	Sites	$\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(km^2)	Peopl/km^2
Morelia	1	3.57	45.85	30.83	1.80	6.51	13.16	4.03	25.49	29.85	85.14	126.24	1497.2	193.03	185
	2	7.53	96.79	65.08	3.80	13.74	27.79	8.51	53.82	63.01	179.73	266.50	3160.8	58.38	1290
	3	12.28	157.76	106.07	6.20	22.39	45.29	13.87	87.72	102.70	292.96	434.38	5151.9	181.31	677
	4	11.36	145.98	98.15	5.73	20.72	41.91	12.84	81.17	95.03	271.08	401.95	4767.2	194.31	585
	5	5.70	73.23	49.24	2.88	10.39	21.02	6.44	40.72	47.67	135.98	201.63	2391.4	122.51	465
	6	11.08	142.32	95.69	5.59	20.20	40.86	12.52	79.13	92.65	264.28	391.87	4647.7	120.16	922
	7	8.75	112.39	75.57	4.41	15.95	32.27	9.88	62.49	73.17	208.71	309.46	3670.3	68.82	1271
	8	7.78	99.97	67.22	3.93	14.19	28.70	8.79	55.59	65.08	185.65	275.27	3264.8	191.11	407
	9	4.51	57.95	38.96	2.28	8.22	16.64	5.10	32.22	37.72	107.60	159.55	1892.3	11.29	3994
	10	0.37	4.78	3.21	0.19	0.68	1.37	0.42	2.66	3.11	8.87	13.15	155.96	56.03	66
Lazaro Cardenas	11	1.32	31.90	21.49	1.26	4.54	9.16	2.81	17.72	20.75	59.15	87.88	1041.2	130.14	101
	12	3.19	77.03	51.89	3.03	10.97	22.11	6.78	42.80	50.11	142.83	212.19	2514.2	89.47	356
	13	1.75	42.30	28.49	1.66	6.02	12.14	3.72	23.50	27.52	78.43	116.52	1380.6	218.13	80
	14	1.53	36.95	24.89	1.45	5.26	10.61	3.25	20.53	24.04	68.51	101.79	1206.0	67.04	228
	15	0.67	16.15	10.88	0.64	2.30	4.64	1.42	8.97	10.51	29.95	44.50	527.23	108.45	62
	16	0.43	10.50	7.07	0.41	1.49	3.01	0.92	5.83	6.83	19.47	28.92	342.70	21.44	203
	17	0.06	1.41	0.95	0.06	0.20	0.41	0.12	0.79	0.92	2.62	3.89	46.13	13.80	42
	18	2.87	69.36	46.72	2.73	9.87	19.91	6.10	38.53	45.11	128.60	191.06	2263.7	205.32	140
	19	2.96	71.48	48.15	2.81	10.18	20.52	6.29	39.71	46.49	132.53	196.90	2332.9	115.60	256
	20	3.10	74.91	50.46	2.95	10.66	21.50	6.59	41.62	48.73	138.90	206.35	2445.0	182.64	170
Apatzingan	21	2.20	21.01	14.08	0.82	2.97	6.02	1.83	11.65	13.64	38.82	57.51	683.76	126.29	174
	22	0.75	7.20	4.82	0.28	1.02	2.06	0.63	3.99	4.67	13.29	19.70	234.16	90.20	84
	23	0.90	8.62	5.78	0.34	1.22	2.47	0.75	4.78	5.60	15.93	23.60	280.54	156.51	58
	24	1.42	13.56	9.09	0.53	1.92	3.89	1.18	7.52	8.80	25.06	37.13	441.38	76.67	185
	25	1.68	16.07	10.77	0.63	2.27	4.60	1.40	8.91	10.43	29.69	43.99	522.92	35.63	473
	26	0.54	5.17	3.47	0.20	0.73	1.48	0.45	2.87	3.36	9.56	14.16	168.32	142.97	38
	27	0.94	8.97	6.01	0.35	1.27	2.57	0.78	4.97	5.82	16.56	24.54	291.76	212.43	44
	28	1.90	18.14	12.16	0.71	2.57	5.20	1.58	10.05	11.77	33.51	49.65	590.25	195.74	97
	29	1.74	16.60	11.13	0.65	2.35	4.75	1.45	9.20	10.77	30.66	45.43	540.13	439.30	40
	30	0.28	2.67	1.79	0.10	0.38	0.76	0.23	1.48	1.73	4.93	7.30	86.78	164.17	17

Table 2. Data of Waste Generation and Population for Each Site of Each City (Continued)[36]

			Waste Production												
	Sites	Population (People)	PP	PE	PET	PS	HDPE	Aluminium	Clear Glass	Green Glass	Brown	Paper	Non-reciclables	Surface	Population Density
		$\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(kg) $\times 10^{-4}$	(km^2)	Peopl/km^2
Leon	31	18.33	26.66	17.99	1.05	3.80	7.68	2.35	14.93	17.35	49.63	73.49	871.39	28.30	6476
	32	3.93	5.72	3.86	0.23	0.82	1.65	0.50	3.20	3.73	10.65	15.78	187.08	33.76	1166
	33	13.22	19.23	12.98	0.76	2.74	5.54	1.69	10.77	12.52	35.80	53.01	628.52	141.51	934
	34	18.71	27.22	18.36	1.07	3.88	7.84	2.40	15.24	17.71	50.66	75.01	889.44	62.06	3014
	35	20.98	30.53	20.60	1.20	4.35	8.79	2.69	17.09	19.87	56.83	84.14	997.75	185.50	1131
	36	2.49	3.62	2.44	0.14	0.52	1.04	0.32	2.02	2.35	6.73	9.96	118.15	91.04	273
	37	23.06	33.54	22.63	1.32	4.78	9.66	2.95	18.78	21.83	62.43	92.45	1096.2	237.32	971
	38	28.96	42.13	28.42	1.66	6.01	12.14	3.71	23.59	27.42	78.42	116.11	1376.8	194.36	1490
	39	7.21	10.50	7.08	0.41	1.50	3.02	0.92	5.88	6.83	19.53	28.92	342.98	189.93	380
	40	6.76	9.84	6.64	0.39	1.40	2.83	0.87	5.51	6.40	18.32	27.13	321.64	56.60	1195
Celaya	41	5.90	142.23	95.53	5.58	20.26	40.78	12.47	78.92	92.38	263.06	390.18	4631.8	41.82	1410
	42	2.90	69.93	46.97	2.74	9.96	20.05	6.13	38.80	45.43	129.35	191.85	2277.4	12.91	2245
	43	4.66	112.42	75.51	4.41	16.02	32.24	9.86	62.38	73.03	207.94	308.42	3661.2	124.90	373
	44	3.52	84.83	56.98	3.33	12.09	24.32	7.44	47.07	55.11	156.91	232.73	2762.7	73.40	479
	45	3.77	90.88	61.05	3.56	12.95	26.06	7.97	50.43	59.03	168.10	249.33	2959.7	8.98	4195
	46	5.76	138.98	93.35	5.45	19.80	39.85	12.19	77.12	90.28	257.05	381.28	4526.1	29.33	1964
	47	6.08	146.65	98.50	5.75	20.89	42.05	12.86	81.37	95.26	271.24	402.32	4775.9	28.35	2145
	48	5.39	130.13	87.41	5.10	18.54	37.31	11.41	72.20	84.53	240.68	356.99	4237.8	107.64	501
	49	5.52	133.08	89.39	5.22	18.96	38.16	11.67	73.84	86.44	246.14	365.09	4333.9	54.73	1008
	50	3.35	80.85	54.31	3.17	11.52	23.18	7.09	44.86	52.52	149.54	221.80	2633.0	71.15	471

into account by the parameters $\sigma^{y}_{d,a}$ and $\sigma^{z}_{d,a}$, which are calculated separately of the model as function of the distance ($x^{\text{distance}}_{d,a}$) between the dumps and the affected regions as follows

$$\alpha^{\text{dispersion}}_{d,a}=\frac{1}{2\ \pi\ \sigma^{y}_{d,a}\ \sigma^{z}_{d,a}\ \text{u}}\exp\left[-\frac{1}{2}\left(\frac{\text{y}_{d,a}}{\sigma^{z}_{d,a}}\right)^{2}\right]$$
$$\left\{\exp\left[-\frac{1}{2}\left(\frac{\text{z}_{d,a}\text{-Hr}_{d,a}}{\sigma^{z}_{d,a}}\right)^{2}\right]+\exp\left[-\frac{1}{2}\left(\frac{\text{z}_{d,a}\text{-Hr}_{d,a}}{\sigma^{z}_{d,a}}\right)^{2}\right]\right\},$$
$$\forall d\in\text{DUMPS},a\in\text{AFFECTEDPOINTS}$$

It should be noted that other parameters that determine the dispersion factor ($\alpha^{\text{dispersion}}_{d,a}$) are the height of receptor ($\text{z}_{d,a}$), the perpendicular distance of receptor ($\text{y}_{d,a}$), the wind velocity (u), the effective height of emitter ($H_{r,a}$), and all these parameters are fixed for any given case study. This way, this article considers the worst case scenario to define the parameters to obtain the dispersion factor, the worst case data are predefined and for this case these are shown in Table 1.[32–36] The dependence of the distance ($x^{\text{distance}}_{d,a}$) for the parameters ($\sigma^{y}_{d,a}$) and ($\sigma^{z}_{d,a}$) are defined in the next relationships

$$\sigma^{y}_{d,a}=0.04x^{\text{distance}}_{d,a}\left(1+0.0001x^{\text{distance}}_{d,a}\right)^{-1/2} \quad \forall d\in\text{DUMPS},a\in\text{AFFECTEDPOINTS} \tag{41}$$

$$\sigma^{z}_{d,a}=0.016x^{\text{distance}}_{d,a}\left(1+0.0003x^{\text{distance}}_{d,a}\right)^{-1} \quad \forall d\in\text{DUMPS},a\in\text{AFFECTEDPOINTS} \tag{42}$$

Conversely, the emission rate of the source ($Q_{g,d}$) is obtained from the total waste in a dump ($W^{\text{total}}_{wn,d}$) multiplied by a conversion factor ($\beta^{\text{pollutant emission}}_{g,d}$); this conversion factor is a function of the amount of waste emitted and burned in case of fire

$$Q_{g,d}=\beta_{g,d^{\text{pollutant}}_{\text{emission}}}\left(\sum_{wn\in\text{WASTE}}W^{\text{total}}_{wn,d}\right), \quad \forall d\in\text{DUMPS},s\in\text{SITES} \tag{43}$$

The concentration of pollutants from the emission is useful to calculate the Probit value for the fatalities due to exposure to toxic gases when a dump is burned, which for a specific pollutant the function is of the form $Y=a+b\ \ln(C^{n}\ t)$. Each pollutant has its own Probit function; that is, each pollutant has given values for the parameters for the Probit function. This function can be linearized in a similar way of the fatalities for leaching. It is noteworthy that one of the most important consideration is that only the pollutant is dispersed in the gas emissions. The data of the Probit function for the pollutant considered is reported in Table 1.[32–36]

$$\vee_{j}\begin{bmatrix} Y^{\text{intoxication linealized}}_{g,d,a,j} \\ C^{\text{toxic concentration}}_{g,d,a}\geq\text{low}C^{\text{toxic concentration}}_{g,d,a,j} \\ C^{\text{toxic concentration}}_{g,d,a}\leq\text{upp}C^{\text{toxic concentration}}_{g,d,a,j} \\ F^{\text{toxic probit}}_{g,d,a}=M^{\text{toxic probit}}_{g,j}C^{\text{toxic concentration}}_{g,d,a}+B^{\text{toxic probit}}_{g,j}\end{bmatrix},\forall \begin{array}{l} g\in\text{GASPOLLUTANT} \\ d\in\text{DUMPS} \\ a\in\text{AFFECTEDPOINTS} \\ j\in\text{INTERVALS2}\end{array}$$

Previous disjunction is reformulated as follows. First, only one segment can be selected

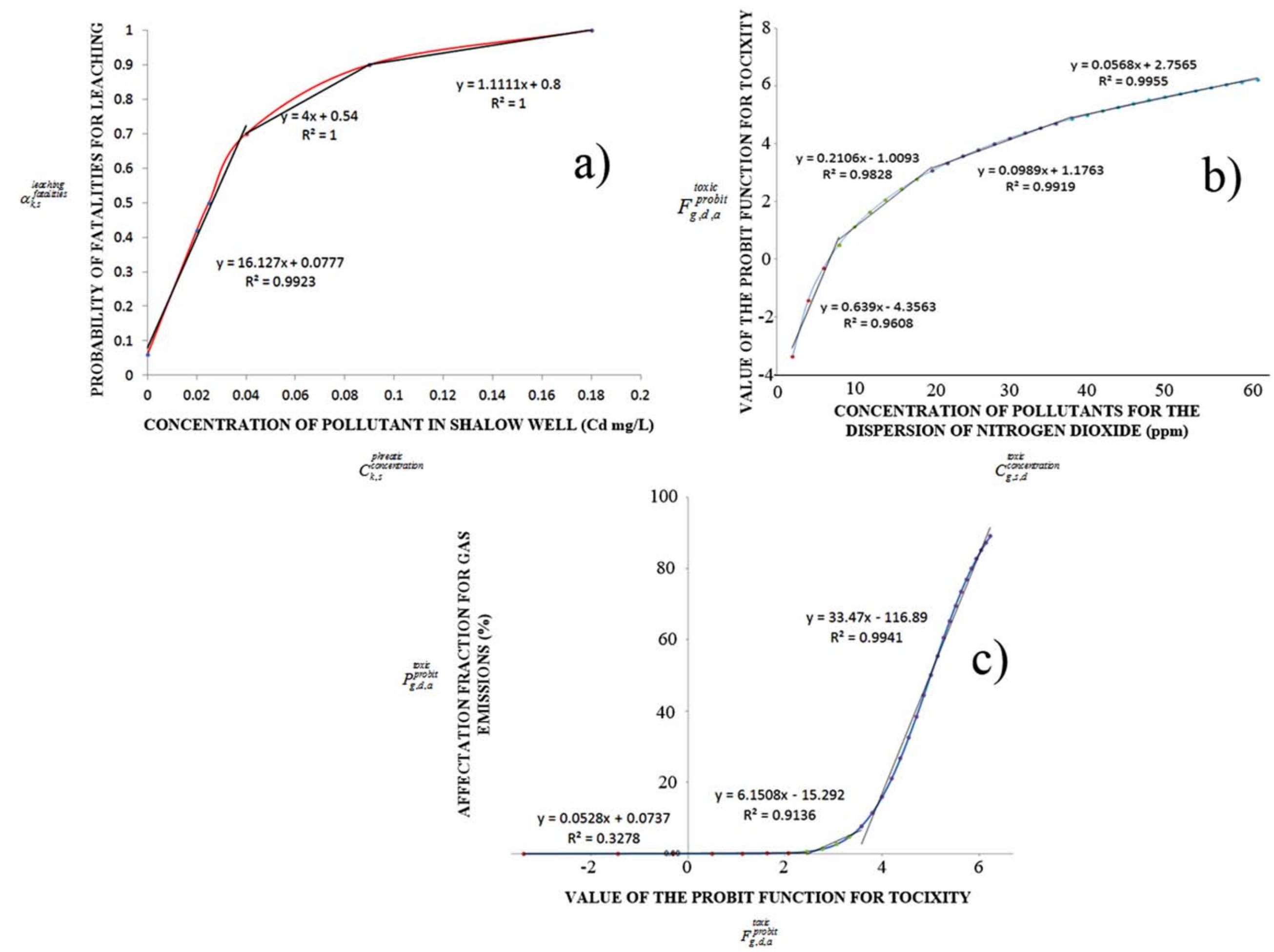

Figure 2. Correlations of experimental data for fatalities for the disjunctions.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

$$\sum_{j\in \text{INTERVALS2}} y_{g,d,a,j}^{\text{intoxication linealized}} = 1, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS} \quad (44)$$

Then, the continuous variables are disaggregated

$$C_{g,d,a}^{\text{toxic concentration}} = \sum_{j\in \text{INTERVALS2}} Cd_{g,d,a,j}^{\text{toxic concentration}}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS} \quad (45)$$

$$F_{g,d,a}^{\text{toxic probit}} = \sum_{j\in \text{INTERVALS2}} Fd_{g,d,a,j}^{\text{toxic probit}}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS} \quad (46)$$

And finally, the constraints are stated as function of the disaggregated variables

$$Cd_{g,d,a,j}^{\text{toxic concentration}} \geq \text{low}C_{g,d,a,j}^{\text{toxic concentration}} y_{g,d,a,j}^{\text{intoxication linealized}}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS}, j \in \text{INTERVALS2} \quad (47)$$

$$Cd_{g,d,a,j}^{\text{toxic concentration}} \leq \text{upp}C_{g,d,a,j}^{\text{toxic concentration}} y_{g,d,a,j}^{\text{intoxication linealized}}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS}, j \in \text{INTERVALS2} \quad (48)$$

$$Fd_{g,d,a,j_{probit}^{toxic}} = \text{M}_{g,j}^{\text{toxic probit}} Cd_{g,d,a,j_{concentration}^{toxic}} + B_{g,j}^{\text{toxic probit}} y_{g,d,a,j}^{\text{intoxication linealized}}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS}, j \in \text{INTERVALS2} \quad (49)$$

In addition, it is needed to propose other equations to obtain the probability of fatalities ($P_{g,d,a}^{\text{toxic probit}}$) as function of the Probit value ($F_{g,d,a}^{\text{toxic probit}}$) for the pollutant in the considered risk. The dependence is nonlinear and has the following form $P=50\left[1+\frac{Y-5}{|Y-5|} erf \frac{|Y-5|}{\sqrt{2}}\right]$. But, this function is easily modeled through the following disjunctive formulation.

$$\vee n \begin{bmatrix} Y_{g,d,a,n}^{\text{intoxication fatalities}} \\ F_{g,d,a}^{\text{toxic probit}} \geq \text{low}F_{g,d,a,n}^{\text{toxic probit}} \\ F_{g,d,a}^{\text{toxic probit}} \leq \text{low}F_{g,d,a,n}^{\text{toxic probit}} \\ P_{g,d,a}^{\text{toxic probit}} = M_{g,n}^{\text{fatalities probit}} F_{g,d,a}^{\text{toxic probit}} + B_{g,n}^{\text{fatalities probit}} \end{bmatrix}, \forall \begin{matrix} g \in \text{GASPOLLUTANT} \\ d \in \text{DUMPS} \\ a \in \text{AFFECTEDPOINTS} \\ n \in \text{INTERVALS3} \end{matrix}$$

Table 3. Data for the Reformulation of the Disjunctions to Obtain the Final Fatalities[32–36]

To Determine $\alpha d_{k,s,i}^{leaching\ fatalities}$ and $\alpha_{k,s}^{leaching\ fatalities}$						
Pollutant	Interval	$M_{k,i}^{probit\ leaching}$	$B_{k,i}^{probit\ leaching}$	$lowC_{k,i}^{phreatic\ concentration}$	$uppC_{k,i}^{phreatic\ concentration}$	Obtained from
Cadmium	1	16.127	0.0777	0	0.04	Figure 2a[33–36]
	2	4	0.54	0.04	0.09	
	3	1.1111	0.8	0.09	0.018	
To determine $F_{g,d,a}^{toxic\ probit}$ and $Fd_{g,d,a,j}^{toxic\ probit}$						
		$M_{g,j}^{toxic\ probit}$	$B_{g,j}^{toxic\ probit}$	$lowC_{g,d,a,j}^{toxic\ concentration}$ (All dumps, affected points)	$uppC_{g,d,a,j}^{toxic\ concentration}$ (All dumps, affected points)	
Nitrogen Dioxide	1	0.639	−4.3563	2	8	Figure 2b[33–36]
	2	0.2106	−1.0093	8	20	
	3	0.0989	1.1763	20	38	
	4	0.0568	2.7565	38	62	
		$M_{g,n}^{fatalities\ probit}$	$B_{g,n}^{fatalities\ probit}$	$lowF_{g,d,a,n}^{toxic\ probit}$ (All dumps, affected points)	$uppF_{g,d,a,n}^{toxic\ probit}$ (All dumps, affected points)	
Nitrogen Dioxide	1	0.0528	0.0737	−3.3858	2.4365	Figure 2c[33–36]
	2	6.1508	−15.292	2.4365	3.5718	
	3	33.47	−116.89	3.5718	6.2293	

Which is algebraically reformulated as follows. First, only one segment can be selected

$$\sum_{n \in INTERVALS3} y_{g,d,a,n}^{intoxication\ fatalities} = 1, \forall g \in GASPOLLUTANT, d \in DUMPS, a \in AFFECTEDPOINTS \quad (50)$$

Then, the continuous variables are disaggregated

$$F_{g,d,a}^{toxic\ probit} = \sum_{n \in INTERVALS3} Fd2_{g,d,a,n}^{toxic\ probit}, \forall g \in GASPOLLUTANT, d \in DUMPS, a \in AFFECTEDPOINTS \quad (51)$$

$$P_{g,d,a}^{toxic\ probit} = \sum_{n \in INTERVALS3} Pd_{g,d,a,n}^{toxic\ probit}, \forall g \in GASPOLLUTANT, d \in DUMPS, a \in AFFECTEDPOINTS \quad (52)$$

And the relationships are stated in terms of the disaggregated variables as follows

$$Fd2_{g,d,a,n}^{toxic\ probit} \geq lowF_{g,d,a,n}^{toxic\ probit} y_{g,d,a,n}^{intoxication\ fatalities}, \forall g \in GASPOLLUTANT, d \in DUMPS, a \in AFFECTEDPOINTS, n \in INTERVALS3 \quad (53)$$

Table 4. Distance and Location for Each Dump with Respect to the Processing Facilities[37]

		Distance Between Dumps and Processing Plants (km)									
		Morelia		Lazaro Cardenas		Apatzingan		Leon		Celaya	
Dump	Site in Which is Located	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8	Plant 9	Plant 10
1	1	3.4	7.7	151.7	159.6	195.4	213.7	222.6	234.1	166.0	168.7
2	3	14.5	1.0	145.0	152.9	206.5	207.0	215.9	227.4	159.4	162.0
3	5	22.4	26.7	170.7	145.0	214.4	199.1	208.0	219.5	151.5	154.1
4	7	28.5	32.7	176.7	184.6	220.5	193.0	247.6	213.4	191.1	148.0
5	11	148.0	152.7	8.7	14.5	190.0	203.2	528.5	539.1	463.0	464.2
6	14	161.8	166.5	22.5	4.3	203.8	192.9	518.3	528.9	452.8	453.9
7	16	166.6	171.3	27.3	33.2	208.6	188.2	547.2	524.1	448.0	449.2
8	20	180.0	184.7	40.7	46.5	222.0	235.2	560.5	571.1	495.0	496.2
9	21	196.0	200.0	587.0	591.6	4.0	21.0	405.6	425.1	342.4	347.0
10	24	209.3	213.2	207.2	188.9	17.3	11.3	395.9	415.3	332.7	337.3
11	27	219.6	223.5	217.5	222.2	27.6	1.0	429.2	405.1	366.0	327.0
12	30	234.7	238.6	232.6	237.3	42.7	59.7	444.3	463.7	381.1	385.7
13	33	211.5	208.0	515.0	521.8	397.5	408.7	7.8	24.5	145.8	150.7
14	35	222.9	218.6	500.0	518.0	408.9	401.9	1.0	17.7	139.0	143.9
15	37	230.0	226.4	533.4	540.2	416.0	394.0	26.2	9.8	164.3	136.0
16	38	234.4	230.9	537.9	544.7	420.4	431.5	30.7	5.4	168.7	173.5
17	41	149.1	152.7	452.7	456.3	328.1	338.7	144.3	153.3	11.0	12.7
18	42	148.0	151.5	451.5	455.2	327.0	337.6	143.2	152.2	9.9	11.6
19	45	159.5	163.0	463.0	448.0	338.5	330.4	136.0	145.0	2.7	4.4
20	49	168.5	172.1	472.1	475.7	347.5	358.1	163.7	136.0	30.4	32.1

Table 5. Efficiency Factors for the Processing Technologies to Treat the MSW[38–42]

Waste	Technology	Product	Production Factor (kg Product/kg Waste; *MJ Electricity/kg waste)
PP	Technology 1 for nanotubes	Nanotubes of 140um diameter	0.11[38]
PE	Technology 1 for nanotubes	Nanotubes of 140um diameter	0.16[38]
PET	Technology 1 for nanotubes	Nanotubes of 140um diameter	0.19[38]
PE	Technology 2 for nanotubes	Nanotubes of 252um diameter	0.32[38]
PP	Technology 2 for nanotubes	Nanotubes of 252um diameter	0.51[38]
PE	Material Recycling 1	Pellet	0.672[39]
PS	Material Recycling 1	Pellet	0.672[39]
PP	Material Recycling 1	Pellet	0.672[39]
PE	Thermal Recycling	Gasoline	0.299[39]
PE	Chemical Recycling	Heat Energy	19.44*[39]
HDPE	Pyrolysis	n-Parafines	0.432[39]
HDPE	Pyrolysis	n-Olefines	0.446[39]
PP	Pyrolysis	Branched Parafines	0.304[39]
PP	Pyrolysis	Branched Parafines	0.333[39]
Paper	Material Recycling 2	New Paper	0.84[40]
Aluminum	Material Recycling 3	Useful Aluminum	1[41]
Clear Glass	Material Recycling 4	New Glass	1[41]
Green Glass	Material Recycling 4	New Glass	1[41]
Brown Glass	Material Recycling 4	New Glass	1[42]
MSW	Mass Burn (Incineration)	Electricity	1.9584*[42]
MSW	Pyrolysis	Electricity	2.0556*[42]
MSW	Pyrolysis/Gasification	Electricity	2.466*[42]
MSW	Plasma Arc Gasification	Electricity	2.9376*[42]
MSW	Conventional gasification	Electricity	2.466*[42]

$$Fd2^{\substack{\text{toxic}\\\text{probit}}}_{g,d,a,n} \le uppF^{\substack{\text{toxic}\\\text{probit}}}_{g,d,a,n} y^{\substack{\text{intoxication}\\\text{fatalities}}}_{g,d,a,n}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS}, n \in \text{INTERVALS3} \quad (54)$$

$$Pd^{\substack{\text{toxic}\\\text{probit}}}_{g,d,a,n} = M^{\substack{\text{fatalities}\\\text{probit}}}_{g,n} F^{\substack{\text{toxic}\\\text{probit}}}_{g,d,a} + B^{\substack{\text{fatalities}\\\text{probit}}}_{g,n} y^{\substack{\text{intoxication}\\\text{fatalities}}}_{g,d,a,n}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS} \quad (55)$$

In this context, the social risk when a dump is burned is obtained multiplying the number of exposed people ($P^{\substack{\text{toxic}\\\text{population}}}_{d,a}$) and the affectation fraction ($P^{\substack{\text{toxic}\\\text{probit}}}_{g,d,a}$)

$$F^{\substack{\text{intoxication}\\\text{fatalities}}}_{g,d,a} = \left(\frac{P^{\substack{\text{toxic}\\\text{probit}}}_{g,d,a}}{100} \right) P^{\substack{\text{toxic}\\\text{population}}}_{d,a}, \forall g \in \text{GASPOLLUTANT}, d \in \text{DUMPS}, a \in \text{AFFECTEDPOINTS} \quad (56)$$

Safety objective function

The safety objective function is based on the total societal risk, which is calculated as follow

$$F^{\substack{\text{total}\\\text{fatalities}}} = \sum_g \sum_d \sum_a F^{\substack{\text{intoxication}\\\text{fatalities}}}_{g,d,a} + \sum_k \sum_s F^{\substack{\text{leaching}\\\text{fatalities}}}_{k,s} \quad (57)$$

where $F^{\substack{\text{total}\\\text{fatalities}}}_{g,d,a}$ represents the total societal risk, which consists of the risk associated with intoxication due to exposure to toxic gases produced by burning waste ($F^{\substack{\text{intoxication}\\\text{fatalities}}}_{g,d,a}$). It should be noticed that the risk due to leaching ($F^{\substack{\text{leaching}\\\text{fatalities}}}_{k,s}$) is also considered.

Case Study

The considered case study corresponds to the west-region of Mexico, where five distributed cities are considered (Morelia, Lazaro Cardenas, Apatzingan, Leon, and Celaya). This case study was previously considered by Santibañez-Aguilar et al.[11]; however, there are some important differences between both cases. The first one is that the paper Santibañez-Aguilar et al.[11] did not consider the transportation between different points inside of a city. The second one, and the most important, is that the previous work did not take into account the possibility to affect the population depending of the distribution of different landfills in cities (i.e., the social risk). Each city is divided in 10 parts called sites, and each site has its own population density and waste generation (see Table 2). The Mexican Institute of Statistics, Geography, and Informatics[36] reported the population and surface of each city, and these data were taken from its database to generate the data for each site.

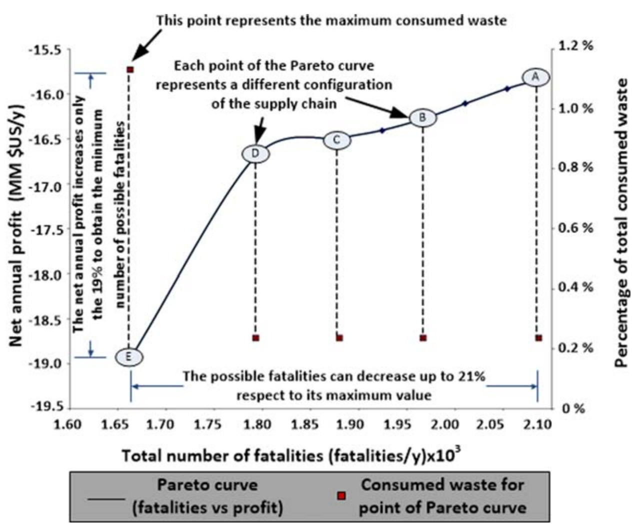

Figure 3. Pareto curve for the net annual profit and the number of fatalities.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

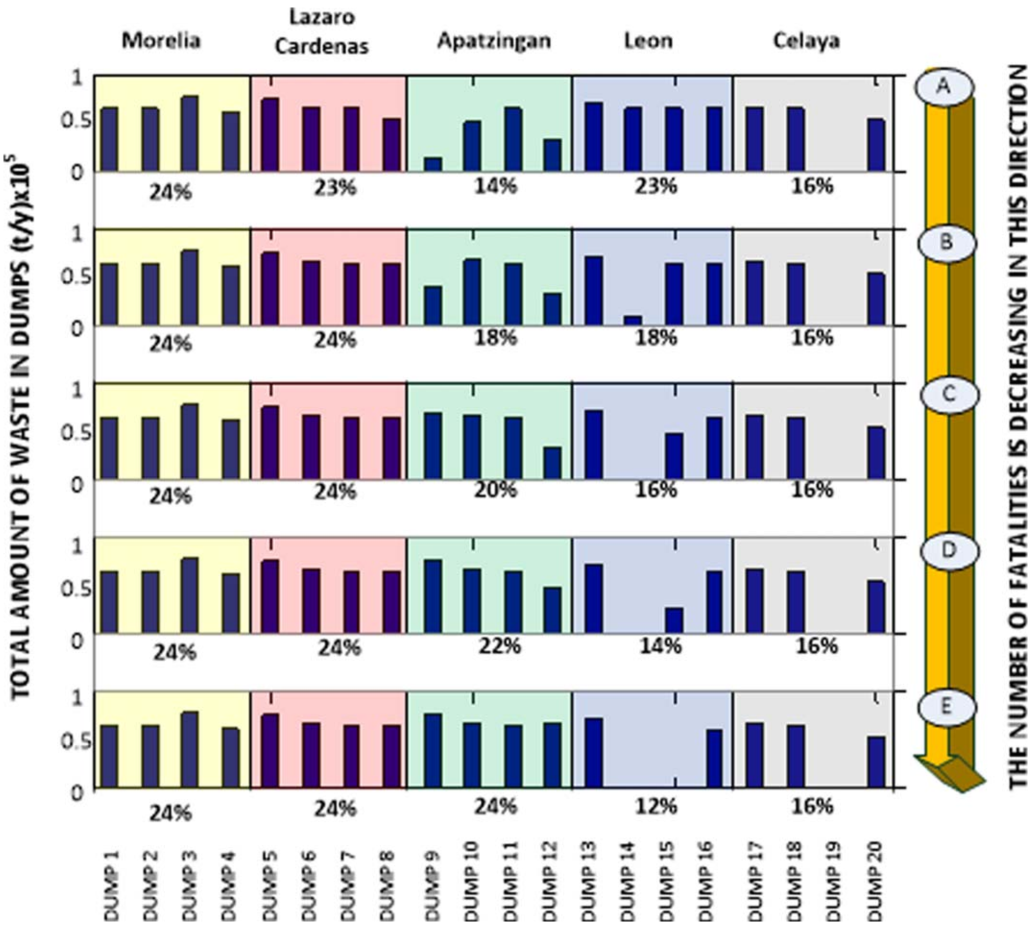

Figure 4. Distribution of the amount of stored waste in each dump for selected points of the Pareto curve of Figure 3.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

In this work, the societal risk considers the fatalities associated to the toxicity of the gas emissions and leaching. In this context, the considered pollutant for the gas emissions was nitrogen dioxide whereas for leaching the considered pollutant was cadmium. The data to generate the functions to assess the societal risk was included in Table 3.[32–36] It is important to note that the data for the disjunctions were experimentally obtained and the corresponding correlations are shown in Figure 2.

It is worth noting that the mathematical formulation does not consider changes in time due to the associated complexity. The data used for the case study are taken from government's institutions accounting for the projected population, which is the main factor associated to the MSW management. In addition, several data used in the mathematical approach does not depend of the time, for example, the conversion for technologies and the data for the Probit curves for the fatalities.

Furthermore, the generated waste is distributed in 20 dumps and can be processed in two processing plants per city, notice that each city has four dumps and these dumps are located in specific sites, and the distance between each dump and the processing facilities is different, the location of the different dumps and the distance between dumps and processing plants are given in Table 4. To obtain these data, the distance between cities was considered.[37] Additionally, Table 5 shows the considered MSW, products and processing routes; the different data for the processing technologies were taken from reported literature.[38–42] This way, Table 6 shows the unit capital and operating costs associated with the considered processing technologies; these costs were estimated from the provided information by the same references of Table 4.

It is important to mention that the technologies are planned to be implemented in the short term future since

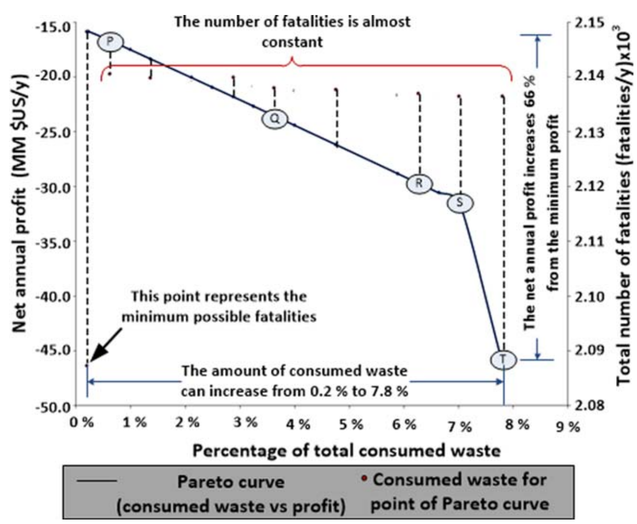

Figure 5. Pareto curve for the net annual profit and consumed waste.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

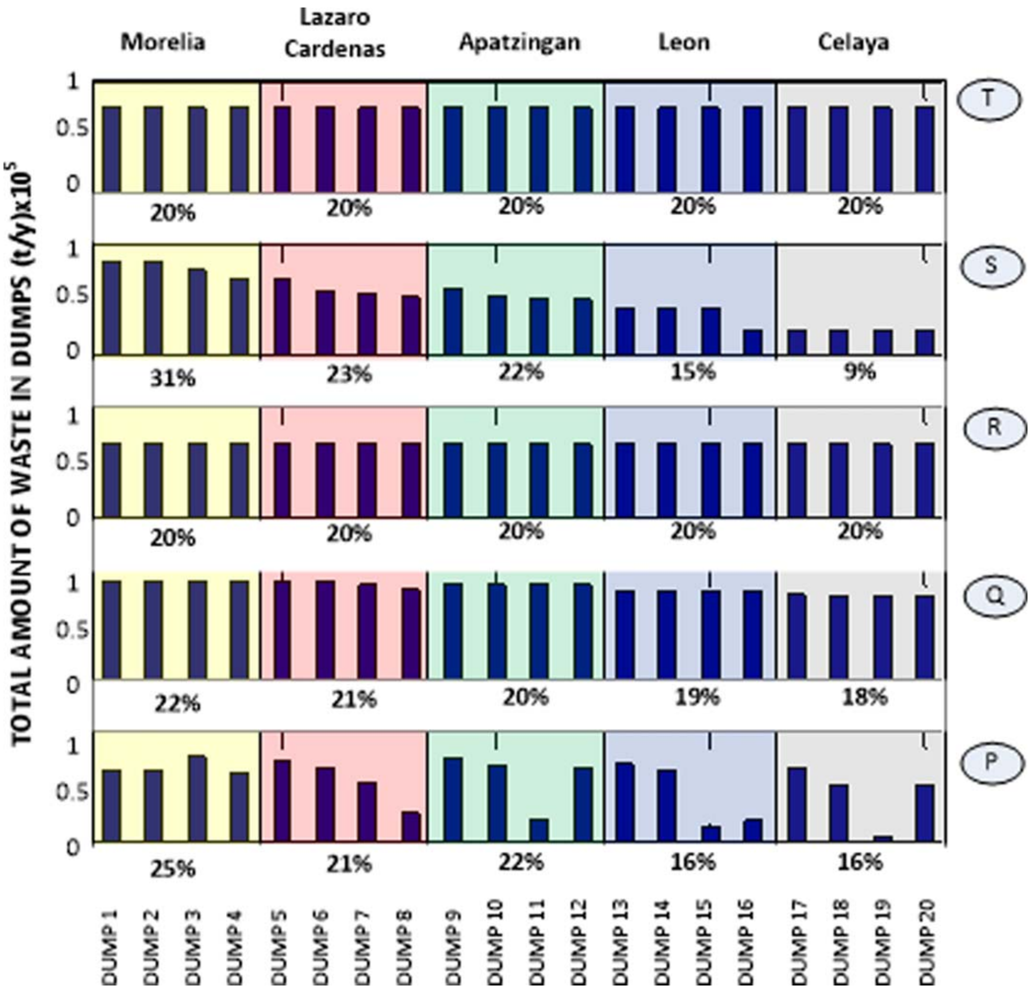

Figure 6. Distribution of the amount of stored waste in each dump for selected points of the Pareto curve of Figure 5.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

there are some preliminary attempts to implement these technologies in a large scale in Mexico.

Results

The mathematical model is a Mixed Integer Linear Programming problem, and it was coded in the software GAMS[43] and consists of 208,681 constraints, 134,710 continuous variables, and 60,240 binary variables taking from 5 to 120 s of CPU time in a processor i7–3720QM at 2.60 GHz with 16 GB of RAM for the solution of each Pareto curve using the solver CPLEX.

The solution approach is based on generating several Pareto curves taking into account only two objectives for each Pareto curve. This way, three different Pareto curves are generated, which are discussed as follows.

The first Pareto curve shows the tradeoff between the societal risk and the economic objective and it is presented in Figure 3. This way, the number of fatalities decreases up to 21% from the maximum number of fatalities while the observed change in the profit is 19%. It is important to note that the fatalities for leaching are the most important in the proposed case study. Furthermore, Figure 3 shows that the consumed waste is almost constant for the Pareto curve of the net annual profit vs. the number of fatalities, determining that the number of fatalities is not function of the consumed waste; however, the number of fatalities is seriously affected for the distribution of waste as can be seen in Figure 4 since this figure shows the distribution of the stored MSW in landfills for each point of the Pareto curve of Figure 3. It should

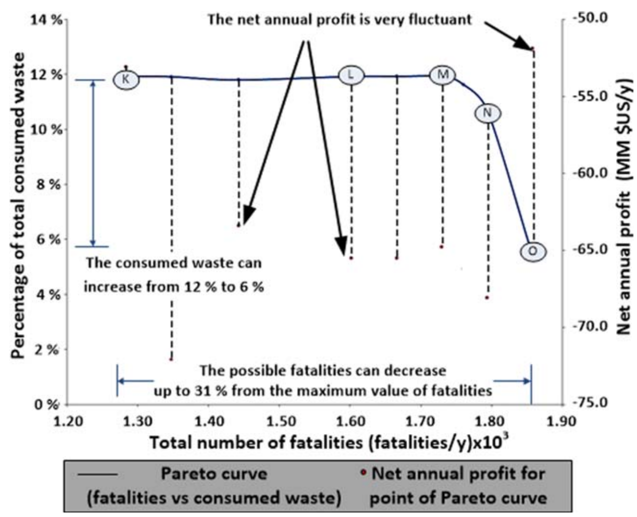

Figure 7. Pareto curve for the number of fatalities and consumed waste.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

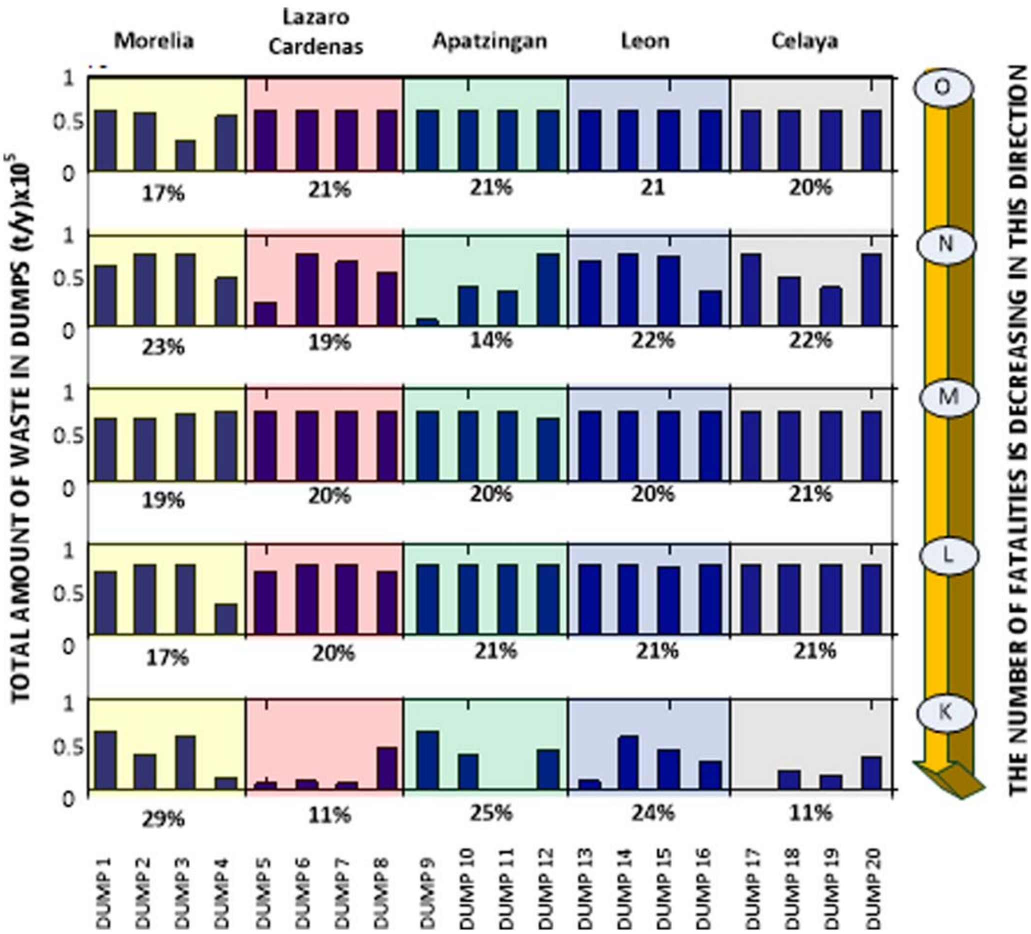

Figure 8. Distribution of the amount of stored waste in each dump for selected points of the Pareto curve of Figure 7.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

be noticed that the main change in the waste distribution is observed in the cities of Apatzingan and Leon because the waste from Dumps 14 and 15 located in Leon city is distributed to Dumps 9 and 12 located in Apatzingan city. This behavior is because the Dumps 14 and 15 are located in the Sites 35 and 37 in Leon city (see Table 3) and these sites have a population density of 1131 and 971 people/km^2, respectively (see Table 2); whereas the Dumps 9 and 12 are located in Apatzingan city in the Sites 21 and 24 (see Table 3) with a population density of 174 and 17 people/km^2, respectively (see Table 2). This is, the waste distribution is prioritized to the sites with lower population density; in this

Table 6. Processing Cost for the Different Technologies and Wastes for the Considered Case Study[38–42]

Waste	Technology	Fixed Capital Cost ($US)	Variable Capital Cost ($US/kg processed)	Operational Cost ($US/kg processed)
PP	Technology 1 for nanotubes	26038000	0.052076	2.6038
PE	Technology 1 for nanotubes	26038000	0.052076	2.6038
PET	Technology 1 for nanotubes	26038000	0.052076	2.6038
PP	Technology 2 for nanotubes	26038000	0.052076	2.6038
PE	Technology 2 for nanotubes	26038000	0.052076	2.6038
PE	Material recycling	3880000	0.0051165	0.388
PS	Material recycling	3880000	0.0051165	0.388
PP	Material recycling	3880000	0.0051165	0.388
PE	Thermal recycling	2057000	0.0059503	0.2057
PE	Chemical recycling	6705000	0.0026819	0.6705
HDPE	Pyrolysis 1	2057000	0.0026819	0.2057
PP	Pyrolysis 1	2057000	0.0026819	0.2057
Aluminum	Material recycling 2	5000000	0.0009	0.09
Glass different types	Material recycling 3	4000000	0.00025	0.01
Paper	Material recycling 4	5000000	0.00044	0.0044
MSW	Mass burn (incineration)	115997700	0.004	0.04
MSW	Pyrolysis 1	86936900	0.004	0.04
MSW	Pyrolysis/Gasification	102593400	0.004	0.04
MSW	Plasma arc gasification	101583800	0.004	0.04
MSW	Conventional gasification	80337800	0.004	0.04

Table 7. Summary of the Results from the Pareto Curves

Case	Minimum Value			Maximum Value		
	Total Fatalities	Annual Profit ($US)	Consumed Waste	Total Fatalities	Annual Profit ($US)	Consumed Waste
Figure 2	1660	-19×10^6	0.24%	2100	-15.7×10^6	1.15%
Figure 4	2087	-46×10^6	0.24%	2140	-15.7×10^6	8%
Figure 6	1250	-73×10^6	5.8%	1860	-52×10^6	12%

	Worst Value	Best Value	• Analyzed case for best case
Total Fatalities	2140	1250	• Minimizing the fatalities vs Maximizing the consumed waste
Annual Profit ($US)	-73×10^6	-15.7×10^6	• Maximizing the annual profit vs Minimizing the fatalities Maximizing the annual profit vs Maximizing the consumed waste
Consumed Waste	0.24%	12%	• Maximizing the consumed waste vs Minimizing the fatalities

case, the average population density of the Dumps 14 and 15 (located in Leon city) is 1051 people/km^2 and the average population density of the Dumps 9 and 12 (located in Apatzingan city) is 95.5 people/km^2, this means that the average of the population density decreases almost 91% while the number of fatalities decreases only 21%. Therefore, a high change in the population density causes a considerable change in the number of fatalities.

The second Pareto curve is shown in Figure 5 and this curve depicts the tradeoff between the depletion of waste and the net annual profit. The behavior of this Pareto curve is similar to the behavior observed in Santibañez-Aguilar et al[11] because the case study and the objectives are similar. However, the results obtained for the other Pareto curves are very different since the safety objective is not considered by Santibañez-Aguilar et al.[11] The differences between the Pareto curve of Figure 5 and the one presented by Santibañez-Aguilar et al.[11] are for the consideration of several sites in each city that influences the transportation costs. Figure 5 shows that the number of fatalities is almost constant when the net annual profit and the consumed waste are taken into account as main objectives; in this way, the number of fatalities changes only 2.5% along the Pareto curve. Furthermore, Figure 6 shows that the amount of the total waste is distributed uniformly in the cities for some points of the Pareto curve of Figure 5 (points T, R, and Q) and is very different for other points of the Pareto curve of Figure 5. However, the number of fatalities is not affected for the distribution of the total waste in the landfills. This is because there are two types of considered fatalities (fatalities for leaching and fatalities for intoxication by gas emissions). In this case, it was observed that the fatalities for intoxication by gas emissions are more affected than the fatalities for leaching because the fatalities for intoxication for gas emissions were too lower with respect to the fatalities for leaching and the total number of fatalities was kept almost constant. This information is useful to conclude that the fatalities for leaching present a low dependence with respect to the waste distribution and this type of fatalities is more affected by the properties of the land such the capacity to filter the pollutants.

The third Pareto curve is presented through Figure 7 and illustrates the tradeoff between the societal risk and the depletion of waste. In this context, the number of fatalities increases from 1250 to 1860, and the consumed waste from 5.8% to 12%. Moreover, the net annual profit changes considerably along the Pareto curve. In order to show the variation of the net annual profit the points O and L of Figure 7 are selected. In these points, the waste distribution changes mainly for the selection of the Dump 4 instead of Dump 3 (see Figure 8). It is important to mention that both dumps are located in Morelia city but in different site (Sites 5 and 7, respectively). In these points, the population densities are very different with values of 465 and 1271 people/km^2, respectively. This way, it is possible to observe that if a dump is selected in a region with a higher population density, the optimal solution presents a lower net annual profit considering the safety and the environmental objectives as main objectives. Additionally, the number of fatalities in point L is lower than the one of point O but the population density is higher in point L than the one of point O; this is, the found behavior is opposite to the one presented in Figure 3. This behavior is due to that the fatalities for intoxication for gas emissions are negligible with respect to the fatalities for leaching in the section of the curve from point M to point K, for this reason the fatalities are almost constant although the waste distribution change.

To compare the different Pareto curves, it is possible to affirm that the optimal solutions obtained from Figure 3 are different to the optimal solutions from Figures 5 and 7. Also, the optimal solutions from Figure 5 are different of the optimal solutions from Figures 3 and 7.

Respect to the societal risk, the best value for the societal risk was of 1250 fatalities and was found in Figure 7 (Maximization of the consumed waste and minimization of the societal risk) while the worst value for the societal risk was of 2140 and it was found in Figure 5 (Maximization of the net annual profit and maximization of the consumed waste). This shows that it is possible to obtain less risky solutions when the safety objective is taken into account. Figure 3 presents values of the societal risk between these two limits (i.e., 1660 and 2100 fatalities).

Additionally, for the economic aspect, the best value of the net annual profit was obtained through Figures 3 and 5. Notice that in both figures the economic objective was considered. However, for the case of the maximization of the net annual profit and the minimization of the societal risk (see Figure 3) it is possible to obtain better profits than the case of the Figure 5 (Maximization of the net annual profit and maximization of the consumed waste). It is important to note that if the decision maker wishes to obtain better profits, the environmental objective should be sacrificed. Conversely, the worst value for the net annual profit was presented when the economic objective was not considered (see Figure 7).

According to the results, the best value for the consumed waste was found in the analysis done in Figure 7 (Maximization of the consumed waste and minimization of the societal risk), this value corresponds to consume 12% of the waste; while the worst value for the environmental objective was obtained through Figures 3 and 5 and it corresponds to consume 0.24% of the waste. It is important to note that the

Pareto curve of Figure 3 does not consider the environmental objective, for this reason, it is possible to obtain a better value for the consumed waste in the Pareto curve of the Figure 5.

It should be noted that the Probit functions are obtained from experimental data previously reported,[32–35] which are shown in Figure 2; therefore, the estimations of fatalities are accurate and realistic.

Finally, Table 7 presents a summary of the results for the considered case study.

Conclusions

This article has presented a mathematical programming formulation for the optimal planning of a distributed system to treat MSW while simultaneously accounting for economic, environmental, and safety objectives. The problem has been mathematically formulated as a multiobjective mixed-integer linear programming problem. The model considers simultaneously the supply chain optimization for the products obtained from MSW while taking into account the social risk assessment through the possible fatalities when a given configuration for a waste management system is implemented. The application of the proposed methodology has been illustrated through a case study of a distributed waste management system in the central-west region of Mexico. The obtained Pareto solutions can provide valuable insights to decision makers in order to select the solution that shows the best compromise among the considered objectives. The proposed methodology is general and can be similarly applied to other case studies. This way, this methodology can be useful to generate the adequate options for the waste management system.

Furthermore, no numerical complications were observed in the solution of the proposed optimization model.

Acknowledgments

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Notation

The symbols used the model formulation have been segregated in indexes, parameters, continuous, and binary variables as follows.

Mathematical notation

$\forall$ = symbol used to define the validity of the equations for a set of given indexes
$\in$ = symbol used to define which elements of a given index are utilized
$\vee$ = symbol used to indicate that a disjunction should be applied to all values for a given index

Indexes

a = index that defines the affected points for gas emissions of pollutants
d = index used for dumps
g = index for the considered pollutant in the gas emissions
i, j, n = indexes used to define the intervals in disjunctions
k = index for the considered pollutants in leaching
p = index used for products
pk = index for processing facilities for waste processing
r = index used for waste processing technologies
s = index that represents the sites in the cities
wn = index for the considered waste in the supply chain

Parameters

$A^{\substack{\text{cap}\\ \text{economies}}}_{wn,pk,r,q}$ = unitary fixed cost associated with the capital of processing technology r within the plant pk
$B^{\substack{\text{cap}\\ \text{economies}}}_{wn,pk,r,q}$ = unitary variable cost associated with the capital of processing technology r within the plant pk
$B^{\substack{\text{probit}\\ \text{leaching}}}_{k,i}$ = intercept to obtain the probability of fatalities for leaching from the Probit curve for a specific interval
$B^{\substack{\text{toxic}\\ \text{probit}}}_{g,j}$ = intercept to obtain the value of the Probit curve for the fatalities for intoxication
$B^{\substack{\text{toxic}\\ \text{probit}}}_{g,j}$ = intercept to obtain the value of the probability for the fatalities for intoxication
$C^{\substack{\text{unitary}\\ \text{product}}}_{p}$ = unitary price of product p at site s
$C^{\substack{\text{unitary}\\ \text{processing}}}_{wn,p,pk,r}$ = unitary operating cost for processing plants
C^{disp}_{d} = unitary cost for waste disposal
C^{sep}_{wn} = unitary separation cost for useful waste
$C1^{\text{transp}}_{wn}$ = unitary transportation cost from sites to dumps
$C2^{\text{transp}}_{wn}$ = unitary transportation cost from dumps to processing facilities
$C3^{\text{transp}}_{wn}$ = unitary transportation cost from processing facilities to consumers
$D1^{\text{transp}}_{s,d}$ = distance from site s to dump d
$D2^{\text{transp}}_{d,pk}$ = distance from dump d to processing plant pk
$D3^{\text{transp}}_{s,pk}$ = distance from processing facility pk to consumer s
$H_{r,a}$ = effective height of emissary
$\text{low}W^{\substack{\text{distributed}\\ \text{plant}}}_{wn,d,pk}$ = lower limit for transportation from dumps to processing facilities
$\text{low}W^{\substack{\text{distributed}\\ \text{routes}}}_{wn,pk,r,q}$ = lower limit for processing depending on the economies of scale
$\text{low}C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,i}$ = lower limit for the concentration in the Probit curve to obtain the fatalities for leaching
$\text{low}C^{\substack{\text{toxic}\\ \text{concentration}}}_{g,d,a,j}$ = lower limit for the intervals for the Probit curve for the gas pollutant g
$\text{low}F^{\substack{\text{toxic}\\ \text{probit}}}_{g,d,a,n}$ = lower limit for the Probit value for each interval to obtain the final fatalities for intoxication
$M^{\substack{\text{probit}\\ \text{leaching}}}_{k,i}$ = pendent to obtain the probability of fatalities for leaching from the Probit curve for a specific interval
$M^{\substack{\text{toxic}\\ \text{probit}}}_{g,j}$ = pendent to obtain the value of the Probit curve for the fatalities for intoxication
$M^{\substack{\text{fatalities}\\ \text{probit}}}_{g,n}$ = pendent to obtain the value of the probability for the fatalities for intoxication
$P^{\text{population}}_{s}$ = population that is affected by leaching in each site
$PD^{\substack{\text{product}\\ \text{consumer}}}_{p,s}$ = product demand in the site s
$P^{\substack{\text{toxic}\\ \text{population}}}_{d,a}$ = exposed people to the gas pollutant
u = wind velocity
$\text{upp}W^{\substack{\text{distributed}\\ \text{plant}}}_{wn,d,pk}$ = upper limit for transportation from dumps to processing facilities
$\text{upp}W^{\substack{\text{distributed}\\ \text{routes}}}_{wn,pk,r,q}$ = Upper limit for processing depending on the economies of scale
$\text{upp}C^{\substack{\text{phreatic}\\ \text{concentration}}}_{k,i}$ = upper limit for the concentration in the Probit curve to obtain the fatalities for leaching
$\text{upp}C^{\substack{\text{toxic}\\ \text{concentration}}}_{g,d,a,j}$ = upper limit for the intervals for the Probit curve for the gas pollutant g
$\text{upp}F^{\substack{\text{toxic}\\ \text{probit}}}_{g,d,a,n}$ = upper limit for the Probit value for each interval to obtain the final fatalities for intoxication
$W^{\text{produced}}_{wn,s}$ = waste production of waste wn in the site s
$y_{d,a}$ = perpendicular distance of receptor
$x^{\text{distance}}_{d,a}$ = distance from the emissary to the affected area or population
$z_{d,a}$ = height of the receptor
$\alpha^{\text{conversion}}_{wn,p,r}$ = conversion factor to determine the amount of obtained product respect to the utilized waste
$\alpha^{\substack{\text{separation}\\ \text{factor}}}_{wn,d}$ = waste separation factor to obtain the available waste
$\alpha^{\substack{\text{filtration}\\ \text{factor}}}_{k,d,s}$ = filtration factor to model the natural sieve of the environment
$\alpha^{\text{dispersion}}_{d,a}$ = dispersion factor that depends of the position for the gas dispersion model
$\beta^{\substack{\text{pollutant}\\ \text{surface}}}_{k,d}$ = factor to obtain the quantity of the pollutant k in the dump from the total amount of waste

$\beta^{\text{pollutant emission}}_{g,d}$ = relationship between the amount of waste emitted and burned in case of fire

$\delta_{s\ \text{quantity-concentration}}$ = conversion factor that is used to obtain the concentration within the water table from the quantity of waste

$\sigma^{y}_{d,a}, \sigma^{z}_{d,a}$ = parameters for the Pasquill Gifford model that depends on the position of the affected surface and dump

Continuous variables

$\text{CAPCOST}^{\text{economies}}_{wn,pk,r}$ = capital cost for the processing route r within the plant pk

$\text{CAPCOST}^{\text{total}}$ = total capital cost for the processing plants

$C^{\text{phreatic concentration}}_{k,s}$ = concentration of the pollutant k in the site s

$C^{\text{dump quantity}}_{k,d}$ = quantity of pollutant in the surface of dump

$C^{\text{toxic concentration}}_{g,s,d}$ = concentration of the gas pollutant g that affects the site s from the dump d

$Cd^{\text{phreatic concentration}}_{k,s.i}$ = discretized concentration of the pollutant k in the site s

$Cd^{\text{toxic concentration}}_{g,d,a,j}$ = discretized concentration of the gas pollutant g that affects the site s from the dump d

$d\text{CAPCOST}^{\text{economies}}_{wn,pk,r}$ = discretized capital cost for the processing route r within the plant pk

DISPCOST = disposal cost for the waste that is sent to landfills

$F^{\text{leaching fatalaties}}_{k,s}$ = fatalities for leaching

$F^{\text{toxic probit}}_{g,d,a}$ = value for the Probit curve to obtain the fatalities for intoxication

$Fd^{\text{toxic probit}}_{g,d,a,j}$ = discretized value for the Probit curve to obtain the probability of fatalities for intoxication

$Fd2^{\text{toxic probit}}_{g,d,a,n}$ = discretized value for the Probit curve to obtain the fatalities for intoxication

$F^{\text{intoxication fatalities}}_{g,d,a}$ = fatalities for the intoxication by the gas pollutant

NETPROFIT = net annual profit for the entire supply chain

OPCOST = total operational cost for the processing facilities

$P^{\text{distributed product}}_{p,pk,s}$ = distributed product from processing facilities to consumers

$P^{\text{product consumer}}_{p,s}$ = total product in the market s

$P^{\text{processing plant}}_{p,pk}$ = obtained product from the utilized waste

$P^{\text{toxic probit}}_{g,d,a}$ = affectation fraction of fatalities for intoxication by a gas pollutant

$Pd^{\text{toxic probit}}_{g,d,a,n}$ = discretized affectation fraction of fatalities for intoxication by a gas pollutant

$Q_{g,d}$ = emission rate when the landfill is burned

REVENUE = obtained revenue for the supply chain based on waste management

SEPCOST = total separation cost for the waste that is processed

TRANSPCOST = total transportation cost for the supply chain

$\text{TRANSPCOST}^{\text{SITES-LANDFILLS}}$ = transportation cost from sites to landfills

$\text{TRANSPCOST}^{\text{LANDFILLS-FACILITIES}}$ = transportation cost from landfills to facilities

$\text{TRANSPCOST}^{\text{FACILITIES-COSNUMERS}}$ = transportation cost from facilities to consumers

$W^{\text{distributed dump}}_{wn,s,d}$ = distributed waste from site s to dump d

$W^{\text{in dump}}_{wn,d}$ = amount of waste inlet to dump d

$W^{\text{total}}_{wn,d}$ = amount of waste stored in dumps

$W^{\text{out dump}}_{wn,d}$ = amount of waste outlet from dump d

$W^{\text{distributed plant}}_{wn,d,pk}$ = distributed waste in each processing facility

$W^{\text{in plant}}_{wn,pk}$ = amount of waste inlet to processing plant pk

$W^{\text{distributed routes}}_{wn,pk,r}$ = distributed waste to processing routes within the processing plants

$Wd^{\text{distributed routes}}_{wn,pk,r,q}$ = distributed waste to the processing routes within the processing plants for each interval of the economies of scale

WASTECONS = ratio for consumed waste with respect to the total produced waste in cities

$\alpha^{\text{leaching fatalities}}_{k,s}$ = probability of fatalities for leaching

$\alpha d^{\text{leaching fatalities}}_{k,s,i}$ = discretized probability of fatalities for leaching

Binary variables

$y^{\text{economies}}_{wn,pk,r,q}$ = binary variable to consider the economies of scale in the processing facilities

$y^{\text{leaching fatalities}}_{k,s,i}$ = binary variable to consider the intervals for the Probit curve to obtain the fatalities for leaching

$y^{\text{intoxication linealized}}_{g,d,a,j}$ = binary variable to consider the intervals for the Probit curve to obtain the Probit value for burning

$y^{\text{intoxication fatalities}}_{g,d,a,n}$ = binary variable to consider the intervals to obtain the fatalities for burning

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