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Optimal waste management during the COVID-19 pandemic

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ABSTRACT

There have been many problems generated by the COVID-19 pandemic. One of them is the worrying increase in the generation of medical waste due to the great risk they represent for health. Therefore, this work proposes a mathematical model for optimal solid waste management, proposing a circular value chain where all types of waste are treated in an intensified industrial park. The model selects the processing technologies and their production capacity. The problem was formulated as a mixed-integer linear programming problem to maximize profits and the waste processed, minimizing environmental impact. The proposed strategy is applied to the case study of the city of New York, where the increase in the generation of medical waste has been very significant. To promote recycling, different tax rates are proposed, depending on the amount of waste sent to the landfill. The results are presented on a Pareto curve showing the trade-off between profits and processed waste. We observed that the taxes promote recycling, even of those wastes that are not very convenient to recycle (from an economic point of view), favoring profits, reducing the environmental impact, and the risk to health inherent to the medical waste.

1. Introduction

One of the main problems as a result of the pandemic is the increase in the generation of some types of waste, mainly medical waste. This type of waste represents a potential risk to health for garbage collectors, health workers, patients, and the general public [1]. Solid waste management was already a problem even before the pandemic, especially in developing countries, due to the lack of infrastructure for waste processing. The existing risk from poor waste management is so high that it is estimated that around 9.2 million people annually die [2].

There are many alternatives and strategies for the management of municipal solid waste (MSW), one of the main trends currently is the conversion of waste-to-energy (WTE) [3,4], using technologies such as gasification, pyrolysis, incineration, among others. However, not all types of waste are convenient to be converted into energy. Metallic waste, for example, has great economic potential, due to the high price at which its derivatives can be sold [5]. In addition, new technologies for waste treatment have been developed in particular for the treatment of waste from COVID-19, such as the processing system for waste from respirators proposed by Zhao and You [6]. Despite the different technologies currently available to MSW, the recycling percentages remain low [7,8]. Different strategies have recently been developed for waste management seeking to increase the amount of waste that is processed, considering different objectives, whether social, environmental, or economic.

In this paper, a multi-objective optimization strategy for MSW treatment is presented. Our approach involves the evaluation of the construction of an industrial park that promotes the intensification of recycling processes, reduces transport costs, and considers different alternatives for MSW, such as recycling, WTE, and landfill disposal. The mathematical model results in a mixed-integer linear problem (MILP) that includes a variable tax rate to increase recycling rates, especially for those wastes with low economic potential, such as the treatment of medical waste, which has increased significantly because of the pandemic.

The work is structured as follows. In Section 2, the related literature is discussed. Section 3 presents the problem statement. In Section 4 the proposed model is presented. In Section 5, the New York case study is shown to represent the applicability of the proposed model. Section 6 shows the discussion of the obtained results. Finally, the conclusion and recommendations are presented in Section 7.
2. Literature review

2.1. Waste management in general

To increase the amount of waste that is recycled, various political and financial strategies have been proposed to promote recycling while increasing the economic and environmental benefits. Zhao and You [9] proposed an optimization system for the Food-energy-water-waste nexus, to reduce the social and environmental impact generated by the COVID-19 pandemic due to the increase in food waste generated. Ko et al. [10] developed a strategy for a hypothetical case in South Korea, where recycling is encouraged through the collection of taxes. These taxes promote the preservation of the environment and the implementation of processes that contemplate process intensification [25] applied to a different supply chain. None of the previous works have considered a strategy that contemplates a circular network that assigns to existing processing centers different amounts of waste. Homayouni and Pishvaee [22] developed a robust multi-objective model for the management of medical waste, considering the satisfaction of one type of sub-waste, which involves the satisfaction of energy and is associated with the consumption of freshwater demands, considering alternatives such as rainwater harvesting, water treatment and recycling, cogeneration, gasification of solid wastes, and algae cultivation. Chen et al., [15] developed a model that considers uncertainty for long-term planning of waste management, which provides information for possible locations of waste processing facilities. The aforementioned strategies coincide with the process intensification approach, where natural or residual raw materials allow maximizing the yield and indirectly the economic benefits [16,17]. From a massive integration framework, this could be especially useful for those wastes with low economic potential and the construction of an industrial park destined for the processing of MSW would be able to promote this type of approach [18].

2.2. Post COVID-19 waste management

Since the beginning of the COVID-19 pandemic, the generation of medical and organic waste has been increasing, which has generated a waste crisis [19] and this has changed the way waste is managed. Govindan et al. [20] developed a MILP model that considers simultaneous economic and social objective functions. This model considers vehicle scheduling, vehicle failure, split delivery, population risk, and fuel consumption to select the optimal transportation routes for waste that minimizes the costs and risk of the population. Valizadeh and Mozafari [21] developed a mathematical model using four cooperative game theory methods, such as the Shapley value, the t value, the central value, and the minimum kernel, employing genetic algorithms for its solution. Under this strategy, incentives are offered to the municipal waste collector contractors, the solutions show that the cooperation between the collectors reduces the total costs, promoting the coalition between the collectors. Homayouni and Pishvaee [22] developed a robust multi-objective model for the management of medical waste, considering the epsilon constraint method and generating a distribution network that assigns to existing processing centers different amounts of medical waste that minimize cost and health risk. Although good results are observed, the distances between each processing center can be large, so transportation costs can be relatively high, depending on the region where it is applied.

There are many opportunities for innovation in the field of process intensification since during the last decade the development of processes in this area has been oriented almost exclusively to large-scale chemical processes [23,24]. Therefore, it is necessary to highlight the relevance of including process intensification in other fields such as urban solid waste management, since the reuse and revaluation of waste are a form of intensification [25] applied to a different supply chain. None of the previous works have considered a strategy that contemplates a circular

**Nomenclature**

**Binary variables**
- \( h_{i,k} \) binary decision variable for which type of technology \( k \) to use for subtype of waste \( j \)
- \( h_{\text{landfill}} \) binary decision variable for what tax rate to use for waste sent to landfill

**Variables**
- \( AS \) sales associated with agriculture
- \( cost_{i,k} \) costs for the implementation of technology \( k \) for subtype of waste \( j \)
- \( cw_{i,j} \) sub waste classified
- \( ES \) sales associated with energy production
- \( f_{i,j,k} \) classified subtype of waste \( j \) that will be processed by technology \( k \)
- \( MS \) sales associated with the processed materials
- \( p_{i,k} \) product obtained from the subtype of waste \( j \) using technology \( k \)
- \( PTC \) transportation cost for products
- \( RMTC \) raw material transport cost
- \( T_{i} \) classified waste \( i \)
- \( T_{\text{landfill}} \) amount of total waste sent to landfill
- \( T_{\text{landfill}}^{\text{higher}} \) waste that will be taxed with a higher penalization

**Parameters**
- \( \lambda_{k,j} \) fixed cost for using technology \( k \) for subtype of waste \( j \)
- \( B_{i,j} \) variable cost for using technology \( k \) for subtype of waste \( j \)
- \( EMPT \) sales per ton associated with electronic material
- \( kf \) annualization factor
- \( SC_{i} \) separation cost
- \( TC_{\text{PTR}} \) total cost per ton of waste transported
- \( a_{i,j} \) existing fraction of each waste \( i \) classified
- \( \beta_{i,j} \) waste separation fraction \( i \) for each type of sub-waste \( j \)
- \( \delta_{\text{min}}^{\text{max}} \) limit for the minimum processing capacity
- \( \delta_{\text{max}}^{\text{max}} \) limit for the maximum processing capacity
- \( \gamma_{i,j,k} \) efficiency factor for processing subtype of waste \( j \) using technology \( k \)
- \( w_{j,k} \) sale price per ton of subtype of waste \( j \) processed using technology \( k \)
framework composed of an intensified industrial park with a wide range of available technologies and a variable rate of green taxes that encourages the processing of hazardous waste and minimizes negative impacts on the environment.

3. Problem statement

The proposed system comprises different types and subtypes of waste, as well as different technologies for each type of waste. Urban centers are considered as the suppliers of waste and the consumers of new materials and energy resources generated in the process, seeking to generate a change in the supply chain from linear to circular, improving the efficiency of the use of waste, coinciding with the concept of circular economy [26] (see Fig. 1). The processing and installation costs of the different recycling units are calculated with a useful life and amortization time of 10 years. The transport providers are considered for the handling of waste and new materials. The intensified industrial park is placed in a specific geographic location (preferably near the source of waste). The separation of waste is considered, representing one of the highest costs of the entire process (see Table S6 in the supplementary material section). The proposed system has two sanitary landfills. In the first one, waste of any type that cannot be processed is sent (due to the processing capabilities of the available technologies), except medical waste that must be sent to a safe landfill, due to the high risk to health that this class of waste represents because of the existing COVID-19 pandemic [27]. Disposing of waste in landfills is cheap economically, but the environmental cost is high. Therefore, to avoid sending large amounts of waste to these landfills, a variable tax rate is proposed depending on the amounts of waste sent to the landfills.

In the proposed superstructure (see Fig. 2), two main types of waste processes are handled, those that are destined to produce new materials (e-waste, metal, glass, plastic, paper and, as a special case, organic waste that is converted to compost) and processes that convert waste into energy (med-waste, organic waste). The formulation of the deterministic mathematical model is general and is not limited by the technologies proposed in this work. The technologies selected for the proposed analysis are discussed below.

3.1. E-waste processing technologies

For the processing of electronic waste, two subtypes are considered, waste from small and large electronic devices [28]. Normally this type of waste contains a great variety of metals with great economic potential. However, due precisely to the large number of materials they contain, the recycling process for this type of material is very limited. The most common process consists of the dismantling and separation of the main pieces, followed by a reduction in size, to end with a magnetic separation that seeks to separate metals from plastics, the separated materials are ready for sale as the raw material used for the production of new electronic or other products [29].

3.2. Metal waste processing technologies

For metal waste, there are more alternatives with different associated costs. For instance, hydrometallurgy is relatively cheap in terms of investment and has a low environmental impact since it does not generate dangerous gases or dust, which makes it ideal for small and medium-scale applications, in addition to having a high percentage of metal recovery, using a two-stage process based on metal leaching [30]. On the other hand, pyrometallurgy has a great disadvantage, since, due to the high temperatures that are handled in this process, secondary materials such as plastic can be lost. Also, it has a high energy requirement and, thus, is not environmentally friendly [31]; however, it is possible to use this technology for large quantities of material, in addition to requiring short processing times [32]. Remelting is the last option proposed for the processing of metal waste in this work, it is probably the simplest process, which involves melting previously separated and compressed metals in large furnaces. Although the energy requirement is high, it is
still lower than obtaining the metals from their principal production route [33]. Subsequently, purification is commonly carried out by electrolysis or simple magnetic separation to eliminate the imperfections present in the new material [34].

3.3. Paper waste processing technologies

The technology used to recycle paper depends mainly on the type of paper to be recycled. For example, waterless technology is a relatively recent technology, and its full potential has not yet been reached, therefore, it is not yet possible to recycle all types of paper with this technology [35], in addition to being highly demanding in terms of electrical energy. On the other hand, recycling paper using water can be used for all types of paper, and energetically speaking is much cheaper than using waterless technology. Although it involves the use of large quantities of water resources, it is more attractive from an economic point of view due to the low associated cost. Although the objective of both technologies is the same (to generate recycled paper), from the economic and environmental points of view they are completely different. The recycled paper from technologies without water generates a favorable environmental impact since it reduces the enormous amounts of water required for recycling paper [36]. However, the price to pay is quite high, since from an economic point of view it is 4.5 times more expensive to invest in waterless technology than in water technology, and the cost to produce a ton of paper is about 30 times higher, which is associated with the high consumption of electrical energy related to waterless recycling machines [35]. This might not be environmentally friendly, so the simultaneous use of both technologies is more favorable.

3.4. Glass waste processing technologies

Glass recycling can be controversial due to how expensive the process is because of the ease with which it fragments, the difficulty of its correct separation, and its low economic potential [37]. Although from an economic point of view it is not attractive [38], its recycling is convenient from an ecological point of view. The technology to be used is remelting because of the simplicity of its process and its efficiency.

3.5. Plastic waste processing technologies

Plastics have enormous potential as a source of chemicals and energy. The revaluation of this type of waste has been one of the most studied [39]. The most common method for the recycling of plastic waste is mechanical recycling [40]. This process typically includes collection, sorting, washing and grinding of the material. Steps may occur in a different order, multiple times or not at all, depending on the origins and composition of the waste [41]. Chemical recycling is especially useful for plastic mixtures that are difficult to separate or when separation is expensive. This technique consists of converting polymers into small molecules for the production of new fuels using a thermo-chemical process thanks to their high hydrocarbon content [41].
additional alternative to chemical recycling is the production of nanotubes through catalytic pyrolysis. This type of process is novel and produces high-value derivatives, although it also requires large investments [42].

3.6. Organic waste processing technologies

In several regions of the world, the incineration of this type of waste has been chosen [84], however, due to how harmful this waste can be for human beings, different technologies are proposed that can be useful for correct processing. Ilyas et al. [43] proposed the use of technologies such as incineration, chemical treatment, and alternative heat treatment for waste disinfection as follows:

- Treatment by incineration: Consists of incinerating the trash at a high temperature between 800 and 1200 degrees Celsius, which kills the pathogen while also destroying 90 percent of the organic materials present. As one might assume, this form of treatment emits a lot of pollutants into the atmosphere, in addition to the pretreatment required for the waste, it may require considerable amounts of energy due to the humidity present in this type of waste [44].

- Chemical treatment: This treatment is based on disinfection treatments, which are commonly employed as a pretreatment in COVID-19 waste and is then followed by mechanical crushing. This approach has good yields, fast action, and a wide sterilization spectrum that can kill the pathogen and the microorganisms present, as well as destroy bacterial spores [45].

- Alternative treatments: The alternative treatments proposed in this article are primarily two, those based on high-temperature pyrolysis techniques and those based on the use of microwaves in medium-temperature ranges.

Any of the treatments described above seeks to reduce the health risk presents in medical waste.

3.6. Organic waste processing technologies

Organic waste has become of special interest at a global level due to its high potential for the production of energy and fuels in a sustainable way [46]. For this type of waste three WTE alternatives are presented: incineration, pyrolysis, gasification, and an alternative option to convert organic waste to compost. The incineration of organic waste can take advantage of the energy contained in organic waste, however, it increases the generation of SO₂, NOx, and other toxic emissions for humans [47]. In comparison, pyrolysis consists of the thermal degradation of substances without the need for combustion reactions to occur, which translates into a lower environmental impact, although its energy efficiency is lower than incineration [48]. Gasification converts the waste into a combustible gas using a gasifying agent, which makes it possible to take advantage of the energy potential of this generated gas, this process generates very low emissions compared with conventional coal combustion [49]. However, the yields obtained and the characteristics of the gases produced in gasification depend, mainly, on the conditions present in the reaction (temperature, pressure, gasifying agent, reaction time) so it is a more complex process than those previously mentioned [50]. As an alternative to energy treatments, it is possible to generate compost from organic waste, through the biological degradation of organic matter. This process is friendly to the environment, although it produces carbon dioxide emissions, these emissions depend mainly on the type of waste and its composition. Producing high-quality compost from MSW can require a lot of energy due to the use of heavy machinery that generates carbon dioxide emissions [51]. However, the use of compost can reduce the need for fertilizers and pesticide chemicals, which implies the reduction of greenhouse gas emissions associated with agricultural production [52].

4. Mathematical model

The formulation of the mathematical model is based on the super-structure presented in Fig. 2, using parameters that allow selecting one process over another when there is more than one alternative for a type of waste. The values for the different parameters can be found in the section of the supplementary material.

4.1. Generated waste in the city

The total waste (TW) produced by the city per year must be separated and classified (see Eq. (1)) into the different types of waste: e-waste, metal, paper, glass, plastic, medical waste, and organic.

\[ T_i = (1 - w_f)TW \cdot \alpha_i, \forall i \in I \] (1)

\[ T^{\text{Landfill}} = w_f TW \] (2)

The above equations allow calculating the quantities of waste to be processed, where \( \alpha_i \) is the existing fraction of each type of waste \( i \) in the selected city (see Table S1). \( T^{\text{Landfill}} \) represents the amount of total waste that cannot be sent to processing (either for reasons of investment or processing capacity), and \( w_f \) represents the fraction of the total waste that cannot be sent to processing (see Eq. (2)). Therefore, \( T_i \) represents the waste that will be processed.

Subsequently, each type of waste must be separated to be processed by the different available technologies for e-waste subtypes, metal subtypes, paper subtypes, glass subtypes, plastic subtypes, medical waste subtypes, and organic waste subtypes (see Eq. (3)).

\[ c_{w_{ij}} = \beta_{ij} T_i, \forall i \in I, j \in J \] (3)

where \( \beta_{ij} \) are the fractions of each subtype of waste \( j \) (see Table S2).

Then, the classified waste is sent to different facilities to be processed (see Eq. (4)).

\[ c_{w_{ij}} = \sum_{k \in K} f_{ik}, \forall i \in I, j \in J \] (4)

where \( f_{ik} \) represents the classified subtypes of wastes that will be processed by the different technologies \( k \) available and compatible for each subtype of waste. The technologies used are shown in Table S5.

4.2. Disjunctions to choose the treatment or processing technology

The selection of one technology or another depends on the objective function. For the optimal selection of the technologies proposed in the model, the following disjunction is established.

\[
\begin{bmatrix}
H_{i,k} \\
\bar{f}_{ik} \geq \delta_{ik}^\text{max} \\
\bar{f}_{ik} \leq \delta_{ik}^\text{min} \\
cost_{ik} = \bar{A}_{ik} h_{ik} + \bar{B}_{ik} f_{ik}
\end{bmatrix}
\] \begin{cases}
\neg H_{i,k} \\
\bar{f}_{ik} = 0 \\
cost_{ik} = 0
\end{cases}, \forall j \in J, k \in K
\] (5)

The decision of what type of technology will be used depends on the Boolean variable \( H_{ij,k} \). If it is true, then, that processing technology is used, while if it is false it is discarded. In the previous disjunction, \( A_{ik} \) and \( B_{ik} \) are parameters used to consider fixed and variable costs. This disjunction can be reformulated as follows:

\[
f_{ik} \geq \delta_{ik}^\text{min} h_{ik}, \forall j \in J, k \in K
\] (6)

\[
f_{ik} \leq \delta_{ik}^\text{max} h_{ik}, \forall j \in J, k \in K
\] (7)

\[
cost_{ik} = kf \left( A_{ik} h_{ik} + B_{ik} f_{ik} \right), \forall j \in J, k \in K
\] (8)

where \( h_{ik} \) is a binary variable, that when its value is 0, the technology is discarded, while when it is 1, it is decided to use that technology. The
values $\delta$ for all cases represent the search limits for the quantities of the material to be processed, these values are established with a lower limit close to 0 and an upper limit depending on the proposed objectives, $k_f$ represents the annualization factor applied to fixed and variable costs.

An example of using the previous disjunction for metal waste is described as follows. The types of proposed technologies compatible with metals are hydrometallurgy, pyrometallurgy, and remelting. Then, to decide if the technology of remelting for iron is used, the decision rests on the value of the Boolean variable $H_{\text{iron, remelting}}$, where if its value is true, that processing technology is used, while if it is false it is discarded.

$$
\begin{bmatrix}
H_{\text{iron, remelting}} \\
\text{f}_{\text{iron, remelting}} \geq \delta_{\text{min, remelting}} \\
\text{f}_{\text{iron, remelting}} \leq \delta_{\text{max, remelting}} \\
\text{cost}_{\text{f, remelting}} = A_{\text{f, remelting}} + B_{\text{f, remelting}} \cdot \text{f}_{\text{iron, remelting}} \\
\mathbf{\vee} \left[ \neg H_{\text{iron, remelting}} \right] \\
\text{f}_{\text{iron, remelting}} = 0 \\
\text{cost}_{\text{f, remelting}} = 0
\end{bmatrix}
$$

Analogously, $A_{\text{f, remelting}}$ and $B_{\text{f, remelting}}$ are parameters used to consider fixed and variable costs. The above disjunction can be reformulated as follows:

$$
f_{\text{iron, remelting}} \geq \delta_{\text{min, remelting}} \cdot H_{\text{iron, remelting}} 
$$

$$
f_{\text{iron, remelting}} \leq \delta_{\text{max, remelting}} \cdot H_{\text{iron, remelting}} 
$$

$$
\text{cost}_{\text{f, remelting}} = k_f \cdot A_{\text{f, remelting}} \cdot H_{\text{iron, remelting}} + B_{\text{f, remelting}} \cdot \text{f}_{\text{iron, remelting}} 
$$

where $H_{\text{iron, remelting}}$ is a binary variable that when its value is 0, the technology is discarded, while when it is 1, it is decided to use that technology. This applies analogously to the other technologies.

It is necessary to point out that the technologies evaluated in the model have been widely studied technologies. Therefore, they can be included in the model through different parameters, such as coefficients for the fixed and variable costs. The different values for the parameters of the fixed and variable costs are shown in Tables S3 and S4.

Finally, all the processed inorganic waste becomes products that can be sold to the city of origin, regardless of the type of technology used for processing:

$$
p_{jk} = \tau_{jk} \cdot f_{jk}, \forall j, k \in K
$$

where $p_{jk}$ is the product obtained from the treatment of the different types of solid waste, $f_{jk}$ are the fractions that according to their respective and compatible technology can convert into products (see Table S5). It is important to highlight that the processed waste such as electronic, metal, plastic, paper, and glass are sent in the form of new materials to the city of origin, while the processed medical waste must be sent to a special sanitary landfill mitigating the risk inherent to this kind of waste. Finally, from the remaining organic waste, it is possible to produce material useful for agriculture. Therefore, the organic waste that is not treated represents an additional source of income.

### 4.3. Costs and sales

The treatment of solid waste requires different levels of investment depending on the type of technology to be implemented or the desired processing capacity, in addition to the expense associated with the transportation of the raw material. Total costs are calculated as follows:

$$
TC = \text{Transport cost} + \text{Treatment cost} + \text{Taxes}
$$

$$
\text{Transport cost} = \text{RMTC} + \text{PTC}
$$

$$
\text{RMTC} = TCPT \left( \sum_{j \in J} T \right) + \sum_{i \in I} (SC_i \cdot T_i)
$$

$$
\text{PTC} = TCPT \left( \sum_{j \in J} \sum_{k \in K} p_{jk} \right)
$$

$$
\text{Treatment cost} = \sum_{j \in J} \sum_{k \in K} \text{cost}_{jk}
$$

where $\text{RMTC}$ is the raw material transport cost (solid waste transport cost), which also includes the separation cost for each type of waste represented by $SC_i$, it is worth noting that by only processing waste from a single city, it is possible to establish a strategic location and leave transportation costs fixed. $\text{PTC}$ is the transportation cost for products, $\text{TCPT}$ is the total cost per ton transported. Table S6 shows the different parameters associated with costs of separation and transport.

For the calculation of taxes, first, two new variables are considered to separate the waste that will be taxed with a lower and a higher penalization. $T_{\text{landL}}$ refers to the waste that will be taxed with a lower penalization and $T_{\text{landH}}$ to the waste that will be taxed with a higher penalization.

$$
T_{\text{landL}} = T_{\text{landH}} + T_{\text{landH}}
$$

Then, the following disjunction is proposed.

$$
\begin{bmatrix}
H_{\text{landH}} \\
T_{\text{landL}} < T_{\text{II}} \\
\mathbf{\vee} \left[ \neg H_{\text{landH}} \right] \\
T_{\text{landH}} > T_{\text{II}} \\
T_{\text{landL}} \leq T_{\text{II}} \\
T_{\text{landH}} \leq T_{\text{II}} (1 - H_{\text{landH}})
\end{bmatrix}
$$

where $T_{\text{II}}$ is the upper bound (for this case, 80,000) for the generated waste for the lower tax, but also it is the lower bound for the higher tax. $T_{\text{III}}$ is the upper bound (for this case, 250,000) for the highest tax. The previous disjunction can be reformulated as follows:

$$
T_{\text{landL}} < T_{\text{II}}, H_{\text{landH}}
$$

$$
T_{\text{landH}} \geq T_{\text{II}} (1 - H_{\text{landH}})
$$

Finally, the taxes can be obtained with the following relationships:

$$
Taxes^{LV} = TPT^{LV} \cdot T_{\text{landH}}
$$

$$
Taxes^{IH} = TPT^{IH} \cdot T_{\text{landH}}
$$

where $TPT^{LV}$ is the lower unitary tax and $TPT^{IH}$ is the higher unitary tax.

$$
Taxes = Taxes^{LV} + Taxes^{IH}
$$

The income will vary depending on the type of material processed and the quantity. In addition to the income associated with the production of energy. Therefore, the income can be calculated as follows:

$$
\text{Revenue} = \sum_{j \in J} \sum_{k \in K} (\omega_{jk} \cdot p_{jk})
$$

where $\omega_{jk}$ is the sale price per ton of waste processed (see Table S7). Finally, the total profit can be calculated as follows:

$$
\text{Total profit} = \text{Revenue} - TC
$$

### 4.4. Objective functions

For the superstructure shown above, it is possible to propose different objectives depending on the case, favoring the economic benefit, reducing the impact on the environment, or favoring the social development are some examples. To minimize the environmental impacts of the decision, the following objectives can be used:

$$
\text{Minimize cost} = \text{RMTC} + \text{PTC} + \text{Taxes}^{LV} + \text{Taxes}^{IH}
$$

$$
\text{Minimize environmental impact} = \sum_{j \in J} \sum_{k \in K} \text{impact}_{jk}
$$

$$
\text{Maximize social benefit} = \sum_{j \in J} \sum_{k \in K} \text{benefit}_{jk}
$$

where $\text{impact}_{jk}$, $\text{benefit}_{jk}$ are parameters that quantify the environmental impacts and social benefits, respectively.
impact, the amount of untreated waste must be reduced (see \( \text{Eq. (8)} \)).

Sanitary landfills present an enormous environmental risk, not only because of the nature of the waste deposited (which also represents a health risk), but also because of toxic chemical seepage into the soil and water supply. These leaks are produced by water precipitation, generating high-risk leachates that may contain volatile organics, chloride, nitrogen, solvents, phennols, and heavy metals. No matter how many barriers, liners, and pipes are installed to try to mitigate risk, landfills will always leach toxic chemicals into the soil and water \([53]\).

Due to waste processing capacities are not unlimited, a certain amount of solid waste must be sent to a landfill. Reducing the amount of waste that is sent would benefit the environment, in addition to reducing the amount of taxes (see \( \text{Eq. (2)} \)).

\[
\min T_{\text{landfill}} \tag{29}
\]

If what is required is to maximize the economic benefit, maximizing the total profit will be needed as follows (see \( \text{Eq. (28)} \)):

\[
\max \text{Total profit} \tag{30}
\]

4.5. Solution procedure

The constrained method was selected for this work \([54]\). This method was implemented initially maximizing the environmental objective function, that is, solving the model considering an unlimited maximum production capacity, which leads to a solution that requires huge areas and investments for the construction of an industrial park capable of processing 100% of the waste generated. Then, the same model is solved seeking to maximize income, which leads to the minimization of the processing capacities and the selection of the cheapest technologies. Here, in addition to sending waste to the landfill, the maximum values obtained from the economic solution, and are added in the form of a restriction to the model that minimizes the environmental impact, now the multi-objective optimization model becomes a single objective, where each economic restriction gives a point on the Pareto curve (see Fig. 3). Here, trade-offs between environmental and economic objectives are observed.

5. Case study

The case study selected for the application of the proposed mathematical model is the city of New York, where the construction of the intensified industrial park in the Staten Island region is proposed. New York City is one of the cities that generates the most waste in the United States \([55]\), in addition to being one of the cities that most has been affected by COVID-19 and the generation of medical waste since the outbreak, in the country on March 3, 2020 \([56]\). In the United States, 2.5 kilograms of medical waste is generated per bed every day \([57]\). Currently, the waste management system is mainly in charge of the New York City Department of Sanitation (DSNY). Waste collection is carried out through public and private contractors where waste is separated into 3 categories: paper, metal/plastic/glass, mixed solid waste (non-recyclable garbage) \([58]\). Regarding recycling, the main facility is the Sunset Park Material Recovery Facility in Brooklyn, where mainly about 75% of the discarded paper, glass, metal and plastic is recycled, however, 80% of the mixed solid waste ends up in a landfill 600 miles from the city. city and only the remaining 20% is converted to energy using incineration \([59]\). During the COVID-19 pandemic, however, the increased demand for medical goods such as masks, gowns, and gogles, along with the fact that domestic trash generated per patient bed is also highly infectious, resulted in a major increase in medical waste. The volume of medical waste is increasing at an exponential rate due to the current COVID-19 pandemic, and hospital staying rooms storage capacity cannot keep up \([60]\). In New York City, there are currently nine medical waste disposal centers with an estimated disposal capacity of 12,000 tons per year, with 60% of the capacity being used to treat highly contagious medical waste under COVID-19 \([61]\). Tables S1, S2, and S6 show the required parameters of the case study for its implementation to the model.

6. Results

The formulation of the mathematical model related to the selected case study (New York City) consists of 317 continuous variables, 63 binary variables, and 341 equations. The resulting model is a mixed-integer linear programming problem (MILP) using the epsilon-constrained method varying the maximum processing capabilities for each of the scenarios. It was solved through the GAMS modeling environment with a solution time of 0.015 s using the CPLEX solver and an AMD 5600x processor at 4.5 GHz with 16 GB of ram at 4000 MHz.

Of all the possible solutions, 4 of them are selected for further analysis (see Fig. 3). Starting with solution A which is a hypothetical case where all the MSW is sent to processing, eliminating the expenses and taxes associated with sending the waste to the sanitary landfill. In this solution, the processing capacity of each one of the recycling facilities would have to be immensely large, which is quite difficult to implement. On the other hand, there is solution B (which remains in the region of the minimum tax rate of 2 USD/ton). In this solution, less than half of the waste is sent to the sanitary landfill, and the processing capacities are not excessively large as it turns out to be in solution A. Solution B is found in the region with the highest tax rate that promotes recycling (5.1 USD/ton) proposed by Munguía-López et al. \([13]\). In this solution, more than 100,000 tons of garbage are being sent to the landfill, however, it is economically viable, since it continues to generate profits, although these can be small. In solution D, which produces annual economic losses, an even greater quantity of the garbage is sent to the landfill, making the investment costs necessary for the implementation of the processing plants exceed the profits that could be obtained (see Fig. 4). On the other hand, the model is solved using data before the pandemic \([62-64]\), in which, as expected, better income is obtained, mainly due to a lower generation of waste with low economic potential, such as organic and medical waste \([5,65]\).

Fig. 4 shows a sample of the distribution of expenses and sales for different solutions. In all scenarios, the highest costs result from the transport and separation of the waste, so it is necessary to highlight that the distance at which the waste source is from the processing center directly affects the viability of the strategy. In this regard, Santibáñez-Aguilar et al. \([5]\) proposed an optimization strategy where the different processing facilities were located in different cities. Therefore, the distances between facilities in some cases were especially large, which meant that some waste such as glass was not convenient to recycle, since the costs of separation and transport exceeded the possible income to be obtained by recycling it. It is observed that the taxes in the first three cases influence significantly, while for the rest of the scenarios it becomes insignificant compared to the rest of the costs. Probably the reduction in the tax rate (solution B) allows increasing the rate of organic and medical waste destined for energy production, which is visible when solution B is compared to solution C (which receives the highest tax rate because it sends large amounts of waste to landfills). The main income comes from the recycling of inorganic waste, so, from an economic point of view, it might be better to discard the waste destined to produce energy and compost, to reduce the costs associated with the separation and treatment of this waste. However, from an environmental point of view, the amount of waste sent to the sanitary landfill would increase dramatically, which would cause a negative environmental and social impact, since within this waste are those generated because of the fight against COVID-19 \([67]\).

6.1. Analysis for e-waste

In this section, the results for metallic residues will be analyzed. Figs. 5 and 8 show the specific flow diagrams for solid waste processing, while Figs. 7 and 10 compare the different costs and sales with the other
types of waste. For solutions B and C, electronic waste is the one that produces the least tax expenses due to the low amount of waste generated annually compared to the other types. However, it is not the one that produces the least profit, mainly because of how expensive the new raw materials generated can be. Therefore, e-waste is an important part of the income generated. It is observed that the change in the tax rate does not affect the amount of e-waste that is sent to be processed. But, in scenario B, although the amounts of e-waste that are sent to the landfill are similar, the tax rate that is applied is the lowest (due to the decrease in the quantities of waste sent from other materials), which drastically increases the profits generated by processing electronic waste.

6.2. Analysis for metals

Next, the results in scenarios B and C for metallic waste are discussed. Undoubtedly, thanks to metal processing, the strategy produces profits, both in scenarios B and C. The metals waste alone produces more than half of the profits (see Figs. 7 and 10). In the prices per ton of new

Fig. 3. Pareto curve for a system of processing facilities based on municipal solid waste during COVID-19.¹³

Fig. 4. Distribution for costs and sales of the supply chain based on solid waste.
Fig. 5. Solution B: analysis for inorganic wastes.
Due to the pandemic of COVID-19, medical waste has gained relevance and volume, so this waste requires special attention. For solution C (see Fig. 9), chemical treatment and alternative thermal treatment are used as medical waste disinfection technologies, which alternatively also produce energy, although, comparing the gains from energy sales, they are very small (see Fig. 4). Table S1 shows that medical waste makes up most of the waste generated by the city, this fraction has increased due to the current COVID-19 pandemic. Therefore, for the strategy presented, it implies that this waste increases more the tax rate. The amount of waste generated is so large that it could be hardly processed completely, thus, a special sanitary landfill for this type of waste is required. In solution B, the waste sent to the special sanitary landfill is reduced by about half. However, the profits do not increase significantly, but it is worth noting that the main benefit of processing this waste lies in the social benefit. In addition, in both solutions, it is suggested to discard incineration, a technology that produces more emissions of toxic chemicals for humans [66].

6.7. Analysis for organic waste

Finally, for organic waste, the process generates two types of income: those associated with the production of material for composition and those related to the production of electrical energy. For any of the solutions, the gains inherent to the agricultural part are always greater. Compared to the results obtained by Zhao and You [6], particularly for food waste (in solutions B and C), the model uses only Pyrolysis for this type of waste, processing only 10% of the food waste generated (see Figs. 6 and 9), however, although in this case food waste is not prioritized, there is a significant reduction in organic waste in general. In scenarios where the higher tax rate is applied, the amount of organic waste processed is minimum, while when a lower tax rate is applied, it takes on greater relevance, and the profits from the processing of this waste become important (see Fig. 4). Similar to the previous analysis, incineration is discarded while pyrolysis and gasification are selected as the technologies for solutions B and C, and as for medical waste, organic waste is one of the most generated, so its processing is essential to achieve a lower tax rate.

The results show that the application of the strategy generates greater processing of previously unprocessed waste, such as those classified as non-recyclable garbage, of which only 20% were processed to be converted to energy, compared to the strategy shown, around 70% of the waste is processed even though it does not represent a significant source of income. This becomes more relevant when a large part of this waste represents a health risk, as is the case of medical waste produced by the pandemic.

7. Conclusions

In this work, a circular framework to address the management of the waste generated by the COVID-19 pandemic employing strategies based on process intensification is presented. This approach incorporates variable green tax rates, which promote the processing of MSW for the production of energy and new materials and minimize environmental and social impacts. The involved objectives include maximizing the economic benefit and minimizing the waste sent to landfills while simultaneously minimizing the social impact generated by the COVID-19 pandemic related to the high risk that the medical waste represents for health. The problem was formulated as a multi-objective mixed-integer linear programming problem. The model considers a wide range of options to process the different types of waste, in addition, it selects and assigns the production capacities for the processing plants of the selected technology. The application of the model was illustrated, selecting New York City in the United States as a case study. The results show that it is feasible to implement an intensified industrial park that...
processes all the waste generated. Furthermore, the variable tax rate promotes waste recycling, maximizing profits even for those wastes with low economic potential. The different Pareto solutions obtained allow the decision-maker to have a wide variety of options to choose the solution that best suits the proposed objectives. The location of the intensified industrial park is key to minimizing transportation costs, which, for waste with less economic potential, can be even higher than the possible sale prices of its associated products. This model can be useful in regions where the municipal solid waste management is not adequate and there is a high risk of exposure to the waste.

As with all strategies, there are limitations that can serve as a starting point for future research, some of which are suggested below:

1. The introduction of standardized Life Cycle Assessment (LCA) methods would offer a better comparison between the different available technologies, from an environmental point of view.

Fig. 6. Solution B: analysis for medical waste and organic waste.

Fig. 7. Solution B: costs and sales distribution for different types of waste.
Fig. 8. Solution C: analysis for inorganic wastes.
A stochastic model would be very useful for the analysis of the supply chain, considering how variable the generation of waste can be in times of pandemics.

Considering the social impact of the generation of jobs associated with the creation of the industrial park would allow the generation of new objective functions with a different approach to the one proposed in this work.

Fig. 9. Solution C: analysis for medical waste and organic waste.

Fig. 10. Solution C: costs and sales distribution for different types of waste.

A stochastic model would be very useful for the analysis of the supply chain, considering how variable the generation of waste can be in times of pandemics.

Considering the social impact of the generation of jobs associated with the creation of the industrial park would allow the generation of new objective functions with a different approach to the one proposed in this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cep.2022.108942.

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