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Optimal Planning of Supply Chains for Multi-Product Generation from Municipal Solid Waste

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In recent years there has been increased the amount of generated municipal solid waste in most of the developing countries, where the waste management systems are not adequate because of lack of organization and infrastructure. A special case is Mexico, where the municipal solid waste management is responsibility for the government; however, the waste management in Mexico is not adequate due to the lack of landfills and culture about of waste separation.

In this regard, this work proposes a mathematical model for the optimal planning of supply chains based on municipal solid waste, where several processing technologies for different waste as well as the total costs for the entire waste management network are considered. This planning problem is mathematically formulated as a multi-objective optimization problem that seeks to maximize the net annual profit (economic objective) and minimize the environmental impact, which is measured through the percentage of the total utilized waste respect to the waste that can be used as raw material.

The proposed optimization approach was applied to a case study in Mexico. The results show that it is possible to implement a supply chain for using municipal solid waste that maximizes the net profit of the network reducing significantly the impact to the environment. Furthermore, the results are shown through a Pareto curve that can be used by decision makers to implement a network for waste processing to obtain multiple products in places where there is not any waste management system at all.

1. Introduction

Municipal solid waste management is a challenge for authorities of cities in developing countries, mainly due to the increasing of waste generation (Abarca-Guerrero et al., 2013). This is a serious problem in countries like Mexico because the size of landfills is not sufficient, the waste disposition is not adequate, and the garbage is mixed with several recyclable and non-recyclable materials, which increases the separation costs and makes the waste recycling process more difficult. In this way, several alternatives have been proposed to solve the waste management problem from different points of view. For example, Antonioni et al. (2012) simulated a two-stage dry flue gas cleaning process for a municipal solid waste incinerator and Kropáč et al. (2013) developed a simulation model for waste-to-energy production. Furthermore, a waste management system can be addressed as a supply chain design problem; in this context, Young et al. (2013) presented an approach for evaluating and designing sustainable supply chains based on waste. Furthermore, Čuček et al. (2012a) presented an approach to reduce the number of objectives in multi-objective optimization, and then Čuček et al. (2012b) applied this approach for biomass-to-energy supply chains. Varbanov et al. (2012) analyzed the energy generation from waste. Šomplák et al. (2013) introduced an interesting approach for facility planning in the field of waste management, where the goal was to obtain the minimum cost for the municipal solid waste treatment in municipalities. In this way, the supply chains focused on the waste management should consider the waste generation, collection, separation, transportation, conversion, distribution, and waste disposal for the

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entire supply chain (see Ng et al., 2013). In addition, another alternative for properly designing waste management systems is to formulate mathematical programming models for their optimal planning, although, the optimal planning problems are not exclusive of the waste management systems since these type of problems can be applied to a large variety of products and these problems can consider several criteria depending on the interest of society. In this context, Hung et al. (2007) presented a review for several models developed to support decision making in municipal solid waste management. Therefore, this paper proposes a general methodology for the optimal planning for a supply chain based on municipal solid waste to obtain multiple products. This methodology considers several stages: the separation and distribution of waste for processing facilities, processing of waste to obtain the desired products and the distribution of the useful products to consumers.

2. Problem statement

The proposed methodology is a multi-objective mathematical optimization model, which allows obtaining the configuration of the waste management system accounting for environmental and economic aspects, and considering several constraints for the different activities involved in the entire supply chain. In this regard, Figure 1 shows the main features of the proposed mathematical model, which takes into account a set of cities that have a given production of waste that can be transported to different processing facilities. The waste from each city is separated to yield different subtypes; for example, polyethylene and chloride of polyvinyl for plastics, as well as green and amber for glasses. When the waste are separated, they can be transported to the processing facilities located in different cities to obtain several products through a set of technologies. Finally, the products are delivered to consumers. On the other hand, each city has a specific demand of products and waste production; the processing plants are located in different regions geographically distributed. Each processing facility has a set of processing technologies to treat different types of waste; also, different operating and capital costs are associated to each processing technology.

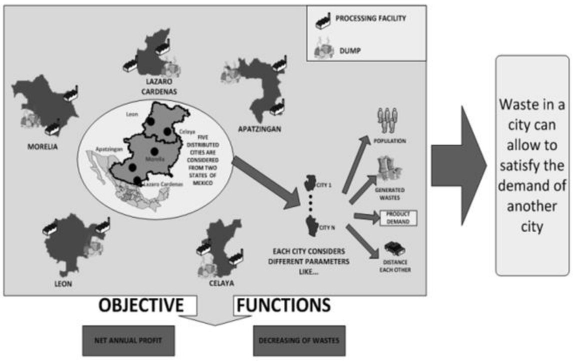

Figure 1: Representation of the considered system for waste management

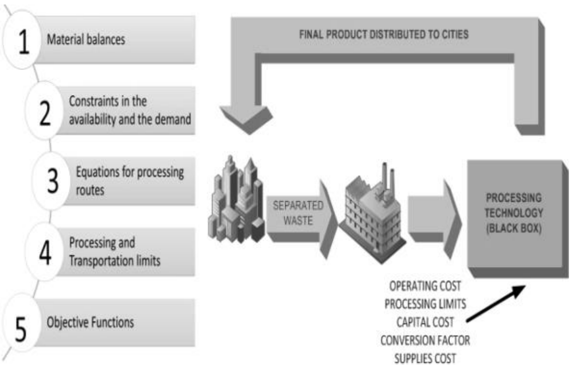

Figure 2: Schematic representation and considerations of the mathematical formulation

3. Model formulation

Prior to present the mathematical model it is necessary to explain the used indexes; in this regard, there are indexes for the locations in the supply chain (processing plants, cities and consumers), and the different waste and processing technologies. The index wn is used for waste, the index *s-w* represents the subtypes of waste, the processing facilities are given by the index p-w and t-w is used to identify the technologies for waste treatment. It is important to note that some indexes have two parts as p-w, t-w, and s-w because they depend on the type of waste (this is t-w means: t-plastic, t-metal and t-non-recyclables*)*. On the other hand, the model formulation is based on several mass balances, constraints for transportation and processing as well as a set of objective functions. The constraints are used to model the different activities involved in the supply chain for waste management such as separation, final disposal, distribution of products, transportation of waste and processing of waste to obtain high added-value products. A general representation of the mathematical optimization model and the processing of waste are shown in Figure 2.

3.1 Constraints for sources in each city

Each city has a specific production of waste that can be separated; however, this separation is not perfect. This means that the useful waste is a portion of the total production of waste in each city. Then, the used waste wn type s-w in the city c ($F_{wn,c,s\text{-}w}$) is lower than the useful waste type s-w in the city c ($\alpha^{sep}_{wn,c,s\text{-}w} F^{total}_{c,s\text{-}w}$). The useful waste wn is equal to the total waste type s-w in the city c ($F^{total}_{c,s\text{-}w}$) multiplied by a separation factor ($\alpha^{sep}_{wn,c,s\text{-}w}$), which is stated mathematically as follows:

$$F_{wn,c,s\text{-}w} \leq \alpha^{sep}_{wn,c,s\text{-}w} F^{total}_{c,s\text{-}w} \qquad \forall wn \in WASTE, c \in CITIES, s\text{-}w \in SUBWASTE \tag{1}$$

3.2 Distribution from cities to processing facilities

When a waste is selected, it is distributed to different processing plants, which are located in several regions. The processing plants are specialized in a given type of waste, this is, plastic, metal, glass or organic waste. Each processing facility has a set of processing routes depending on the treated waste. Then, the selected waste in any city c ($F_{wn,c,s\text{-}w}$) is equal to the delivered waste from the city c to the specific processing plant for each waste pw.

$$F_{wn,c,s\text{-}w} = \sum_{p\text{-}w \in PROCPLANT} F^{plant}_{wn,c,p\text{-}w,s\text{-}w} \qquad \forall wn \in WASTE, c \in CITIES, s\text{-}w \in SUBWASTE \tag{2}$$

It should be noted that there are a lot of types of processing facilities and each processing plant has a set of processing technologies depending on the waste. For example, each plastic plant has a set of technologies to treat plastics; in this regard, for each waste wn there is a set of technologies to treat all subtypes of waste s-w, and these technologies are defined with the index t-w.

3.3 Technologies used for waste regeneration in processing plants

Waste in processing plants is distributed to different processing technologies, and depending on the selected technology is possible to produce different products. The amount of waste from the city c ($F^{plant}_{wn,c,p\text{-}w,s\text{-}wn}$) is assigned to the different technologies ($F^{tech}_{wn,p\text{-}w,t\text{-}w,s\text{-}w}$) as follows:

$$\sum_{c \in CITIES} F^{plant}_{wn,c,p\text{-}w,s\text{-}w} = \sum_{t\text{-}w \in TECHNOLOGIES} F^{tech}_{wn,p\text{-}w,t\text{-}w,s\text{-}w}, \qquad \forall w \in WASTE, p\text{-}w \in PROCPLANT, s\text{-}w \in SUBWASTE \tag{3}$$

Notice that an index for products is not needed because each technology is specific for one product.

3.4 Mass balances in processing facilities

The model considers the transformation of waste to products, which occurs within processing plants. The conversion processes involve usually nonlinear relationships; however, this paper considers an efficiency factor for each technology and type of feedstock ($\alpha^{prod}_{wn,t\text{-}w,s\text{-}w}$), which helps to obtain the amount of yielded product ($P_{wn,p\text{-}w,t\text{-}w,s\text{-}w}$) from an amount of given feedstock ($F^{tech}_{wn,p\text{-}w,t\text{-}w,s\text{-}w}$) avoiding numerical complications in the optimization process:

$$P_{wn,p\text{-}w,t\text{-}w,s\text{-}w} = \alpha^{prod}_{wn,t\text{-}w,s\text{-}w} F^{tech}_{wn,p\text{-}w,t\text{-}w,s\text{-}w}, \qquad \forall wn \in WASTE, p\text{-}w \in PROCPLANT, t\text{-}w \in TECHNOLOGIES, s\text{-}w \in SUBWASTE \tag{4}$$

3.5 Mass balances in splitters after processing plants

The obtained products from a given processing facility ($P^{city}_{wn,p\text{-}w,t\text{-}w,s\text{-}w}$) can be distributed to different markets ($P^{city}_{wn,p\text{-}w,c,t\text{-}w,s\text{-}w}$) as follows:

$$P_{wn,p\text{-}w,c,t\text{-}w,s\text{-}w} = \sum_{c \in CITIES} P^{city}_{wn,p\text{-}w,c.t\text{-}w,s\text{-}w}, \qquad \forall wn \in WASTE, p\text{-}w \in PROCPLANT, t\text{-}w \in TECHNOLOGIES, s\text{-}w \in SUBWASTE \tag{5}$$

3.6 Mass balances in the mixers before the markets

Before each market c, there is a mixer for each product; in this point, the streams of the same product are mixed to obtain the total amount of such product for a specific market. Therefore, the sum of products arrived to the city from the processing facilities is equal to the total product distributed in the city:

$$\sum_{\text{p-w}\in\text{PROCPLANT}} \mathrm{P}^{\text{city}}_{\text{wn,p-w,c.t-w,s-w}} = \mathrm{PT}^{\text{city}}_{\text{wn,c,t-w,s-w}}, \quad \forall \text{wn}\in\text{WASTE}, \text{t-w}\in\text{TECHNOLOGIES}, \text{c}\in\text{CITIES}, \text{s-w}\in\text{SUBWASTE} \tag{6}$$

3.7 Constraints for the demand of products in markets

On the other hand, the total product in a market ($\mathrm{PT}^{\text{city}}_{\text{wn,c,t-w,s-w}}$) must be always lower than or equal to the demanded product ($\mathrm{PD}^{\text{city}}_{\text{wn,t-w,c,s-w}}$) as follows:

$$\mathrm{PT}^{\text{city}}_{\text{wn,c,t-w,s-w}} \leq \mathrm{PD}^{\text{city}}_{\text{wn,t-w,c,s-w}}, \quad \forall \text{wn}\in\text{WASTE}, \text{t-w}\in\text{TECHNOLOGIES}, \text{c}\in\text{CITIES}, \text{s-w}\in\text{SUBWASTE} \tag{7}$$

3.8 Economic objective function

The model formulation takes into account several equations to obtain the different costs associated to the entire supply chain including the capital ($\mathrm{CostCap}^{\text{total}}$) and operating ($\mathrm{CostOp}^{\text{processing}}$) costs for the facilities as well as the transportation cost ($\mathrm{CostTransp}^{\text{processing plant}}_{\text{city}}$ and $\mathrm{CostTransp}^{\text{city}}_{\text{processing plant}}$), separation cost ($\mathrm{CostSep}^{\text{total}}$) and final disposal cost ($\mathrm{CostNSep}^{\text{total}}$); all these costs are utilized to calculate the value of the economic objective function. Additionally, the net profit (NetProfit), as objective function, is defined as the revenues from sales ($\mathrm{C}^{\text{sales}}$) minus all previously mentioned costs.

$$\mathrm{NetProfit} = \mathrm{C}^{\text{sales}} - \mathrm{CostSep}^{\text{total}} - \mathrm{CostCap}^{\text{total}} - \mathrm{CostOp}^{\text{processing}} - \mathrm{CostTransp}^{\text{processing plant}}_{\text{city}} - \mathrm{CostTransp}^{\text{city}}_{\text{processing plant}} - \mathrm{CostNSep}^{\text{total}} \tag{8}$$

It is important to note that for the presented case study, the responsible for the waste management system is the municipal government. Therefore, all the involved costs are supported by the municipalities; in this context, during the recycling process, the highest costs are associated to separation and disposal. If the recycling process is not implemented, private companies collect the waste and the people have to pay for the waste disposal to dumps (because no separation is required), which implies severe environmental problems.

3.9 Consumed waste

The consumed waste is considered an environmental and social objective function, because when the waste is not reused, this is deposited in dumps causing significant environmental problem that affect the society. In this regard, the percentage of the consumed waste ($\mathrm{Consume}^{\text{waste}}$) is given as follows:

$$\mathrm{Consume}^{\text{waste}} = 100 \times \frac{\sum_{\text{wn}\in\text{WASTE}} \sum_{\text{c}\in\text{CITIES}} \sum_{\text{p-wn}\in\text{SUBWASTE}} \mathrm{F}_{\text{wn,c,p-wn}}}{\sum_{\text{wn}\in\text{WASTE}} \sum_{\text{c}\in\text{CITIES}} \sum_{\text{p-wn}\in\text{SUBWASTE}} \alpha^{\text{sep}}_{\text{wn,c,p-wn}} \mathrm{F}^{\text{total}}_{\text{c,p-wn}}} \tag{9}$$

4. Results

The proposed mathematical model was applied to a case study from the central region of Mexico, where there is a lack of a waste disposal culture as well as an inadequate waste disposal infrastructure and organization. In this context, five cities are considered (see Figure 1), where five main types of waste are taken into account, these waste are paper, plastics, glasses, metals and others, which are divided into eleven sub-waste (three types of glasses, five types of plastics, aluminium, one type of paper and one type of mixed unrecyclable waste that are processed through fourteen processing routes; these routes are considered to treat different types of waste (two technologies to obtain carbon nanotubes, four types of material recycling, pyrolysis for plastics, pyrolysis for mixed waste, chemical recycling, thermal recycling, incineration, plasma arc gasification, conventional gasification and a type that considers gasification and pyrolysis simultaneously). The processing routes were taken from the reported data by Hur et al. (2003) and Young (2010). It should be noted that in the proposed case study the waste are separated after the collection steps at the moment in which the waste are deposited in the landfills. Also, the separation activity is done by private companies that collect the waste from the city, which is a common case in Mexico. The methodology involves a multi-objective optimization mathematical programming problem; in this case, the methodology considers two objectives, the first one is the economic and the second one is the environmental. These objectives contradict each other; in this context, the best solution depends on the point of view because the best environmental solution is the worst economic solution. In addition, the best economic solution is the worst environmental solution; in this regards, the best solution depends on the decision makers.

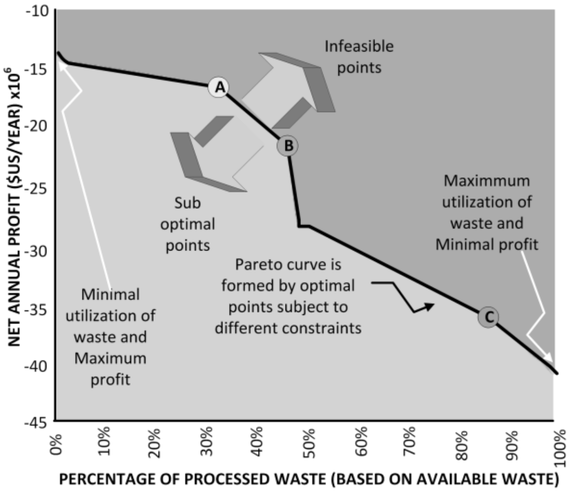

Figure 3: Pareto curve for the net annual profit and the total consumed waste

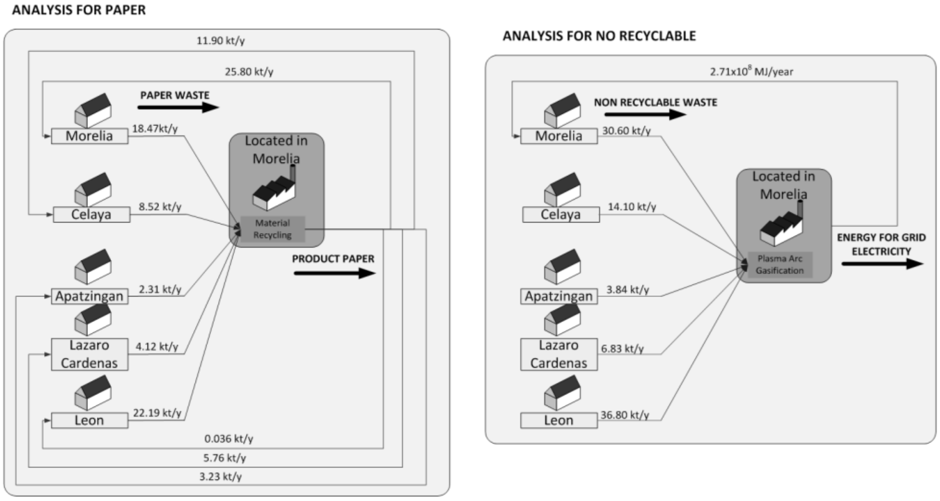

Figure 4: Configuration of the supply chain for point C of the Pareto curve of Figure 3 for paper and no recyclable waste

Results are shown in the Pareto curve of Figure 3; notice that the Pareto curve only provides information about the compromise between the objectives to select one alternative. In this case, the economic objective is the net annual profit and the environmental objective is the percentage of processed waste; the best value for profit is obtained when the percentage of consumed waste is the smallest (this is because for this case the municipal government has not to pay for the waste collection and separation). Each point corresponds to different configurations for the waste management system and the proportion of each utilized sub-waste changes depending on the location of the processing facilities and the availability of the raw materials. In this context, the x-axis represents the percentage of processed waste based on the available waste, where the available waste is the amount of waste that can be processed to obtain products after the separation and disposal steps. The Pareto curve shows that the net annual profit is always negative because the collection, separation and final disposal costs are considered. Therefore, for the implementation of this type of systems the disposal cost must be absorbed by the municipal government; however, it is important to observe the global impact in the entire supply chain.

Figure 4 shows the configuration of point C for paper and no recyclable waste (notice that other waste is consumed too). This configuration shows that the non-recyclable waste is processed in a plant located in Morelia city by arc gasification. It should be noted that the numbers before the processing facility represent the amount of waste that is transported to the processing plant to obtain a given amount of useful product; in this way, the amount of useful product is represented by the numbers after the processing plant. Additionally, currently Morelia city does not have any processing plant to treat the non-recyclable waste. In addition, waste paper is selected to obtain recycled material in one processing plant in the city of Morelia, this is due to low transportation costs because Morelia city is in the centre of the considered geographic region. It is important to note that the proposed methodology provides information about the amount of waste that should be processed and the amount of obtained products.

5. Conclusions

This paper has presented a mathematical formulation for the optimal planning of a supply chain for using municipal solid waste considering simultaneously economic and environmental objectives; this formulation has taken into account the supply chain optimization based on municipal solid waste and the application of the proposed methodology was illustrated through a case study of a distributed system in five cities located in the central-west region of Mexico. Furthermore, it is important to mention that the model is applicable in places where the waste management system is not developed or not exists, and this model is focused on the design step. The results show that it is possible to implement a processing system for multiproduct generation from municipal solid waste that minimizes the overall management cost while maximizes the reused waste. Additionally, the Pareto curve shows that the amount of consumed waste is opposed to the net annual profit. Finally, the information of the profit and consumed waste as well as the configuration of the entire supply chain can be useful to the decision makers to implement a waste management system.

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