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Applied system dynamics to municipal solid waste management: Valorization as landfills alternative for the state of Hidalgo, México

Dinámica de sistemas aplicada al manejo de residuos sólidos urbanos: Valorización de residuos como alternativa a los rellenos sanitarios para el estado de Hidalgo, México

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Abstract

Municipal Solid Waste management is one of the main problems in developing countries due to intensive use of landfill and open dumps. Several technologies have been tested to give added value to municipal solid wastes in developed countries, such technologies, also known as valorization processes, includes recyclable materials recovery, biodigesters and waste to energy processes to take advantage of organic and inorganic phases respectively. This paper analyzes the impact to required confinement volume and electric generation ascribe to Municipal Solid Waste Valorization scheme as a substitute for Municipal Solid Waste Landfills in the State of Hidalgo, México.

***Keywords*:** Municipal solid waste; landfills; waste to energy; valorization; system dynamics.

Resumen

El manejo de los residuos sólidos municipales es uno de los principales problemas en los países en vías de desarrollo debido al uso intensivo de los rellenos sanitarios y los vertederos a cielo abierto. Diversas tecnologías han sido probadas para dar valor agregado a los residuos sólidos municipales en los países desarrollados, tales tecnologías, también conocidas como procesos de valorización, incluyen la recuperación de materiales reciclables, biodigestores y procesos de recuperación de energía de los desechos, a fin de aprovechar la fase orgánica e inorgánica de los residuos respectivamente. El presente trabajo analiza el impacto al volumen requerido de confinamiento y la generación eléctrica debido al esquema de Valorización de Residuos Sólidos Municipales como sustituto de los rellenos sanitarios para residuos sólidos municipales en el Estado de Hidalgo, México.

***Palabras Claves*:** Residuos sólidos urbanos; relleno sanitarios; energía a base de residuos; valorización; dinámica de sistemas.

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1. Introduction

In recent decades, Municipal Solid Waste Management has become one of the main challenges of developing countries society, given its growing generation and social, economic and environmental impacts. Shared responsibility is required to develop a zero-emissions policy and technological development is needed.

Reference [1] review and summarize available Municipal Solid Waste (MSW) as fuel technologies, where biological and thermochemical treatments are the most used. Thermochemical treatments with low oxygen usage, as pyrolysis and gasification, improves Waste-to-Energy (WtE) efficiency [2], in case of electricity production only WtE facilities net electric efficiency may reach values up to 30–31%, higher efficiency may be possible to reach when advanced technical solutions are applied in large–scale plants [3]. This scenario shows how MSW management is an opportunity rather than a challenge to obtain commodities, where collecting and transportation logistics are the current challenges [4]. This MSW management opportunity feature scenario is evident in studies such as those conducted in Nigeria [5], Kathmandu Valley [6] and Quito, Ecuador [7].

México is among the ten countries with higher MSW production worldwide [8], been landfill the main deposition system for MSW [9]. The Government of the State of Hidalgo, located in Valley of México metropolitan area, has developed a mitigation policy to ensure MSWLF space demand for the next twenty years through reuse, recycling, composting, Biogas and Refused Derived Fuel (RDF) to power generation encouragement [10].

System dynamics is a discipline that provides distinctive concepts and tools to allow the study of accumulation and feedback effects in complex systems. The system dynamics models focus on the structure and behavior of systems composed of interacting feedback loops. System dynamics models focus on the disequilibrium dynamics and complexities, through decision rules, stocks and flows. The strength of system dynamics consists in its ability to examine how the system structure influences decisions and how systems react to these decisions over time, allowing exploration of futures and justify the development of possible scenarios. Therefore, system dynamics is useful for representation of population dynamics and its effect on output variables, MSW generation is a clear example. Forecast tools for this variable have been developed as a support for analysis, selection and improvement of strategies, policies and technologies for suitable MSW management [11–13]. Also, system dynamics models have been developed to achieve those tasks [14, 15].

This research analyzes the system dynamics of Municipal Solid Waste management technologies combinations available nowadays in México. The MSW management techniques for combination are: 1) Municipal Solid Waste Landfills (MSWLF), 2) Compacted Municipal Solid Waste Landfill (CMSWLF), 3) Landfill Gas Collection (LGC), 4) Biodigesters (BD), 5) Recycling and 6) Waste to Energy (WtE). Confinement required space and electric generation are evaluated under system dynamics approach with a 20-year planning horizon.

From MSW management techniques mentioned above, MSWLF is taken as the baseline since it only involves wastes deposition, without material recovery or power generation, therefore it presents the greatest quantifiable impacts [16]. On the other hand, mainly impacts reductions are relevant for energy recovery from wastes technologies, such as Biodigesters [17] and Waste to Energy [18].

2. Methodology

Municipal Solid Waste generation is dependent on population growth rate function (P_{GR}), for the State of Hidalgo, this function is represented by equations:

$$MSW = \int P_0 P_{GR} G_F dt. \tag{1}$$

$$P_{GR} = 59.661 - 2.9 \times 10^{-2} t, \tag{2}$$

where P_0 corresponds to the population at time zero of the planning horizon, 2,858,360.00 inhabitants for this research; G_F is solid waste generation factor per capita reported by Instituto Nacional de Estadística y Geografía (INEGI) [19]. Equation 2, Population Growing Rate (P_{GR}) as a function of time, is also obtained from population growth rate data available at INEGI for the State of Hidalgo as of the year 2000.

Two technological approaches, currently available or in development in the State of Hidalgo, are analyzed. First, standard techniques like Municipal Solid Waste Landfill (MSWLF), Municipal Solid Waste Landfill with Landfill Gas Collection (MSWLF w/ LGC), Compacted Municipal Solid Waste Landfill (CMSWLF) or Compacted Municipal Solid Waste Landfill with Biodigester (CMSWLF w/ BD) technologies. Second, valorization techniques as MSWLF substitute, applying state of the art Waste to Energy, recycling and Biodigester combined processes as key multifunctional technologies, in accordance with the circular economy concept of product added value, where this property is maintained as long as possible, minimizing waste and resource consumption [20].

To quantify the required confinement volume and electric production, a stock-and-flow model was developed and built using VENSIM® Professional (version 5.11A) modeling software from Ventana Systems, Inc. Figure 1 shows the stock-and-flow model general structure.

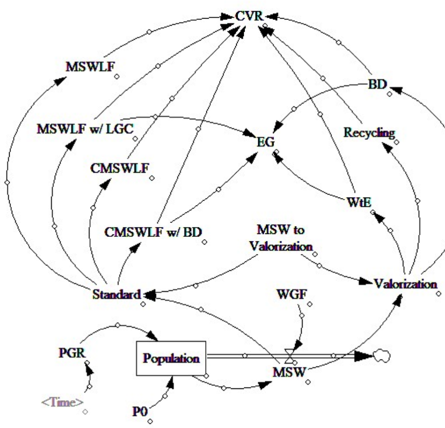

Fig. 1. Simplified stock and flow model for MSW management.

The model structure allows independent evaluation of technological approaches. Combination of both approaches is suitable for evaluation. Auxiliary variable ‘MSW_to_Valorization’ controls this function assigning MSW flow supplied to each approach, ‘Standard’ or ‘Valorization’, values from 0 to 1 are set, where “0” represents the case when all MSW flow goes to Standard treatment such as MSWLF, and “1” represents full treatment of MSW through valorization approach. Additional auxiliary variables are used to split, Standard MSW flow and Valorization MSW flow, between available processes and technologies within each approach.

The model quantifies electric generation (EG) and confinement volume required (CVR) at evaluation period, it does not take into account volume reduction process of previously confined wastes and rural wastes due to sources dispersion. Table 1 shows waste specific volume and electric generation parameters per ton of MSW, those parameters allows CVR and EG variables quantification for each technological approach. Specific volume refers to confined MSW (MSWLF, MSWLF w/ LGC) or treated MSW (CMSWLF, BD, WtE). Electric generation factors incorporate fuel low heating value (LHV) and process efficiency on basis of one ton of MSW.

Technology	Specific Volume (m^3 ton^{-1}) [21–23]	Electric generation factor (kWh ton^{-1}) [24]
MSWLF	3,3	0
MSWLF w/LGC	3,3	390
CMSWLF	1,5	0
BD	0,9	668
WtE	0,039	1100

Table 1: Model parameters.

3. Results and discussion

3.1. *General model*

Annual confinement volume required for both technological approaches is shown in Figure 2. According to model restrictions, MSWLF technologies, with or without LGC, are the most confinement volume demanding technologies, this agreement with the behavior of reported and simulated landfills for large cities, such as Shanghai, where availability of confinement sites is a major issue [25]. Confinement volume is significantly reduced when other MSW management technologies are applied. Mechanical compaction generates MSWLF and CMSWLF confinement volume difference, this difference increases when organic phase separation from MSW is carried out to a biodigester process as raw material.

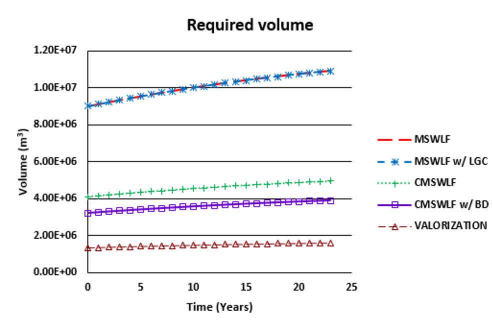

Fig. 2. Annual required confinement volume for technological approaches.

Valorization technological approach minimizes confinement required volume since recyclable materials recovery, organic phase separation for BD and inorganic phase energy recovery via RDF production for WtE processes. Required confinement volume growth rates are a function of population growth rate and specific volume of confined waste or treatment effluent. Differences between required confinement volume growth rates for the MSW management techniques like MSWLF (81,875 m^3/year) and Valorization (12,235 m^3/year) are meaningful, due to valorization technological processes, WtE and BD, where the effluents are ashes and organic matter respectively. Those effluents are suitable for further treatments to increase their added value and merge to available productive chains. Growth rates also allow local budgets estimation since the average final disposal cost for MSWLF in Mexico is \$20.83 USD ton [26].

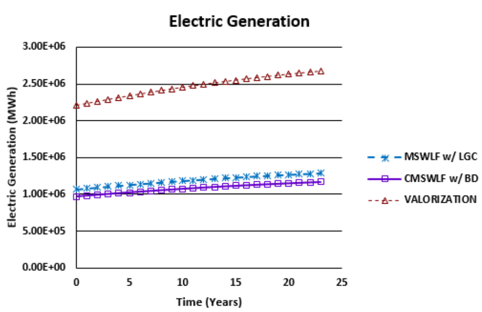

Fig. 3. Electric generation profiles.

Figure 3 shows MSWLF with LGC, CMSWLF with BD and valorization electric generation profiles. Valorization electric generation profile incorporates BD biogas and RDF low heating value for power generation through reciprocating generators and WtE steam turbine processes. These profiles take into account continuous operation for the three MSW management schemes, however it is known that MSWLF with LGC and CMSWLF with BD electric generation slowdown is function of the organic phase amount at landfill closure year [17], this behavior gives rise to the analysis of available Valorization schemes, where both MSW phases, organic and inorganic, are suitable for electric generation [27, 28]. For the present work, electric generation from valorization is 107% and 128% higher than MSWLF with LGC and CMSWLF with BD respectively.

3.2. *Scenario. State of Hidalgo towards valorization*

A Valorization plant construction and start-up scenario to handle State of Hidalgo MSW evaluation is carried out with the developed model for a 20–years planning horizon from plant start–up. Valorization plant includes organic phase separation to be provided as raw material for a BD process to generate biogas, recyclable materials recovery, carried out before RDF production, and biogas and RDF systems for electric generation via a reciprocating generator and WtE steam turbine respectively. Scenario evaluation contemplates a three years construction period, in which MSWLF operate as usual. At the end of the construction period, a one-year transition period is established to full transfer of MSW from MSWLF to Valorization plant.

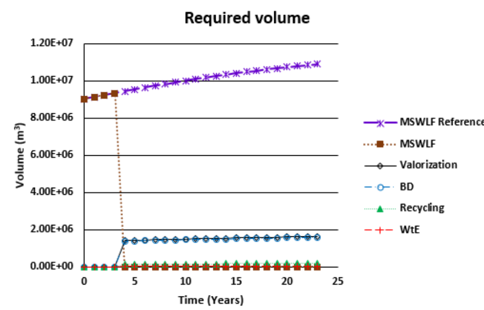

Fig. 4. Required confinement volume profile scenarios.

Figure 4 shows the required confinement volume for valorization processes sub products or effluents, MSWLF and MSWLF Reference profiles. MSWLF Reference profile represents 'No valorization plant construction and start-up' scenario. An 85.1% reduction of total confinement volume requirement is detected. From the remaining fraction, only 3% of the required volume corresponds to WtE sub products, mainly ashes, as can be seen from Figure 5.

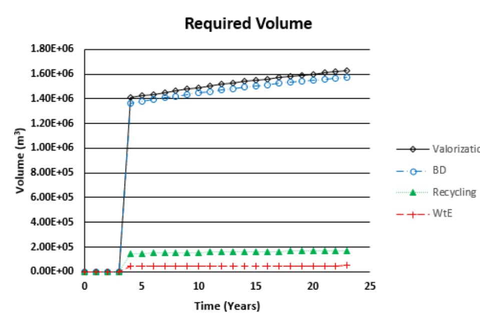

Fig. 5. Required confinement volume for Valorization sub products profile.

It should be noted that volume savings by recyclable material recovery correspond to 1.56% of the reference volume or 3.32% of the inorganic MSW fraction. Recyclables volume do not contribute to Valorization volume requirements since these materials are sent to specialized recycling plants for high or low-performance applications [29], other municipal solid waste dynamic models, as the one developed for Bangkok [30], highlight recyclables recovery technologies regardless of selected MSW management scheme.

As mentioned early BD effluents are suitable for treatment as raw material for fertilizers and other products. This strategy leaves ashes from the WtE process as the only effluent from Valorization, thus, a reduction of the required confinement volume of 99.5% is feasible.

Figure 6 presents the electric generation contributions from BD and WtE. Biodigester process produces 46% of the total electric plant production. The remaining 54% corresponds to the Waste to Energy process. Valorization plant annual total electric production covers the State of Hidalgo local demand by 8.0%.

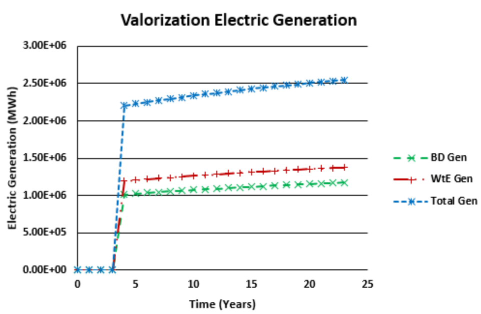

Fig. 6. Valorization electric generation profile.

Moya et al. [7] present the city of Quito, Ecuador case study, which in terms of population is comparable to the State of Hidalgo scenario defined above. City of Quito study case defines a valorization scheme where organic and inorganic phases are used for electric generation. According to Moya et al. model monthly electric production is around 300 GWh. A 200 GWh monthly electric generation was calculated with the model developed in the present work. The difference lies on model premises, MSW composition, MSW generation per capita and recyclable recovery schemes. Both, City of Quito and State of Hidalgo valorization cases, are consistent as landfills substitutes due to the combined technologies that involve MSW Valorization approach. This consistency is also achieved by Ayodele et al. [5] study for twelve different allocations in Nigeria, where combined WtE and BD systems show the best electric generation.

4. Conclusions

System dynamics is an evaluation tool for high impact technology projects. It allows to visualize and quantify technology and policies impacts of infrastructure development projects such as the MSW management approaches described in this paper.

Municipal Solid Waste management sustainability is linked to required deposition volume reduction, electric generation, and recyclable material recovery. Although materials recovery for recycling contributes to MSW Sustainable Management, its contribution is lower compared to BD and WtE processes. Municipal Solid Waste generation and treatment analysis, where traditional landfills and valorization schemes are studied, gives rise to shared objectives that reflect the viability of technological transfer for sustainable management.

Municipal Solid Wastes Valorization technological approach presents the best performance in terms of required confinement volume and electric generation versus common municipal solid waste management schemes used in México, releasing pressure over another scarce resource: soil. The construction and start-up of Municipal Solid Waste Valorization plants, with a recovery scheme for recyclable materials, biodigester, and Waste to Energy processes, have a great potential to drastically mitigate MSW deposition and energy demand of urban centers.

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