Waste Management 28 (2008) S7–S13

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

# Mathematical modeling to predict residential solid waste generation

Sara Ojeda Benítez [a,*], Gabriela Lozano-Olvera [a], Raúl Adalberto Morelos [b], Carolina Armijo de Vega [c]

[a] Engineering Institute, UABC, Boulevard Benito Juárez y Calle de la Normal S/N, Col. Insurgentes Este, C.P. 21280, Mexicali, Baja California, Mexico
[b] CESUES Superior Studies Center, San Luis R.C. Sonora, Mexico
[c] Engineering Faculty, UABC, Km 103, Carretera Tijuana-Ensenada, C.P. 22860, Ensenada, Baja California, Mexico

ARTICLE INFO

*Article history:*
Accepted 28 March 2008
Available online 25 June 2008

ABSTRACT

One of the challenges faced by waste management authorities is determining the amount of waste generated by households in order to establish waste management systems, as well as trying to charge rates compatible with the principle applied worldwide, and design a fair payment system for households according to the amount of residential solid waste (RSW) they generate. The goal of this research work was to establish mathematical models that correlate the generation of RSW per capita to the following variables: education, income per household, and number of residents. This work was based on data from a study on generation, quantification and composition of residential waste in a Mexican city in three stages. In order to define prediction models, five variables were identified and included in the model. For each waste sampling stage a different mathematical model was developed, in order to find the model that showed the best linear relation to predict residential solid waste generation. Later on, models to explore the combination of included variables and select those which showed a higher $R^2$ were established. The tests applied were normality, multicolinearity and heteroskedasticity. Another model, formulated with four variables, was generated and the Durban–Watson test was applied to it. Finally, a general mathematical model is proposed to predict residential waste generation, which accounts for 51% of the total.



## 1. Introduction

Municipal solid waste (MSW) generation and management is an issue of worldwide interest; it constitutes a cycle made up of several stages which are closely related.

Solid waste generation also represents a socio-environmental problem and is the result of a production and consumption cycle. In this way, all manufactured, commercialized and consumed products are finally converted – at least partially – into waste. Since consumption is unstoppable and ever increasing, waste production is becoming gradually more important and its disposal is a problem that seriously threatens the sustainable development of society today. When analyzing material flow, from the moment raw materials are extracted to manufacture goods until they turn into waste, it is observed that the problem of solid waste arises at the very moment that the raw materials are extracted. Waste still is produced throughout the manufacturing process and it becomes even worse when consumers discard the remaining part of the product, which is no longer useful to them.

The cycle starts with the production of consumer goods and continues with the generation, storage, sweeping, collection and final disposal of solid waste. Studies conducted on solid waste management are focused on the complete cycle or only on some stages. Generally, the purpose of the studies is to obtain benefits, such as introducing a more sustainable management of municipal solid waste, promoting citizen participation and well-being, contributing to environmental conservation, among others. This work is focused on the generation and characterization of residential solid waste, since those parameters are very important for decision-making in regard to the planning and design of solid waste management systems and final disposal.

Like many other countries, Mexico faces a great challenge in managing its (MSW) due to its industrial growth, population increase, habits, improvement of family welfare, and migration from rural to urban areas. For such reasons, the Federation, through its Secretariat of Environment, Natural Resources (*Secretaría del Medio Ambiente, Recursos Naturales*, SEMARNAT), in coordination with the National Institute of Ecology (*Instituto Nacional de Ecología,* INE), set the regulations, laws, and goals to control contamination in the country.

The problem of MSW generation is a cause for concern in Mexico, because the management and control of MSW has been inadequate for years and management and disposal of municipal solid waste has never been under full control.

* Corresponding author. Tel.: +52 686 5664150.
*E-mail address:* sojedab@uabc.mx (S. Ojeda Benítez).

0956-053X/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.wasman.2008.03.020

The management of MSW has been extensively discussed and reported in a large number of studies, trying to find relationships and the best plans to solve the problem of MSW, from its collection to its final disposal.

Modeling is a tool used for the planning and management of municipal waste. Tanskanen and Melanen (1999) propose a mathematical model for the planning of solid waste management; Fabricino (2001) proposes a mathematical model to be applied to the integrated management of municipal waste, from its generation to its transportation and final disposal, emphasizing the percentage of material that can be recovered.

There are many researchers who have carried out simulations and have modeled MSW management systems in several parts of the world using mathematical models; among them we can mention Mac Donald (1996) who examined the state-of-the-art of solid waste (SW), analyzing 14 mathematical models based on economic optimization criteria. The problem is that such models require large quantities of data and, as a result, they are more suitable to be applied during the stages of planning and set up. In another study conducted by Lund (1990), he analyzes the alternatives for final disposal in a sanitary landfill through a linear optimization model.

Jacobs and Everett (1992) proposed mathematical models to analyze the recovery of recyclable components. In a more recent research study, Everett and Shahi (1996) proposed an administration model for the setting up of compost plants. Meanwhile, Everett and Modak (1996) also developed a general model aimed at specifying the more convenient methods for MSW collection and disposal for each region.

The model proposed by Chang et al. (1996) addresses the problems of collection vehicles and traffic control, which includes models of non-linear equations and solves them by using interpolation and division algorithms.

In another study, Fabricino (2001) points out that the complexity of models lies in the need to understand the large quantity of parameters and data used, which can not be immediately quantified to do the initial planning of MSW. The proposed model solves or tries to solve the problem of preliminary decision-making prior to the planning phase and its economic optimization. Its application proves how it can be used to assess the economic advantages of MSW collection and disposal.

Salhofer (2000) designed a model aimed at trying to estimate industrial and commercial waste generation in Vienna. This model is based on a matrix, which is applied to sort the type of business that generates the waste by commercial/industrial sector, and is based on the number of employees. The results are comparable to data from similar studies.

In a study conducted in Chile by Orccosupa (2002), he analyzes the relationship between the production of residential solid waste per capita and socio-economic factors. In his model, Orccosupa links economic income against electric power consumption and applies the theory of the Environmental Kuznets Curve, which relates per capita income and the pressure exerted on the environment, all this aimed at reducing residential solid waste (RSW). Beigl et al. (2004) developed a model to identify the parameters that help to account for the current situation and to estimate the generation of MSW in various European cities. Results have shown that this model can be a useful tool to support decision-making regarding municipal solid waste; however, they also showed that the proposed model must be statistically refined (especially the composition modulus) for its application in other contexts.

Beigl et al. (2008) conducted a review of the literature regarding the models developed to estimate waste generation in order to classify the models according to the following criteria: regional scale, modeled waste streams, independent variables and method.

The use of mathematical models can be an alternative to deal with the problem of municipal waste management. In this sense, Sheshinski (2001) emphasizes the importance of creating a mathematical model to deal with the problem of solid waste and the care one should take when creating it.

The mathematical relationship among the amount of solid waste, its transport, cost, treatment, etc., is difficult to construct due to the large quantity of variables involved, and the changing nature of such relationships, which were analyzed by Fabricino (2001) and Sheshinski (2001). The importance of the different parameters in the analysis must be clearly stated in detail so as to ensure that we are using optimal values; otherwise, we would document a wrong relationship between functions and wrong estimates.

For all those reasons, this paper will deal with the problem of solid waste generated per day in an urban community and the need to formulate a mathematical model so as to explain the variables related to this problem. Therefore, the purpose of this research is to develop a mathematical model that explains the variables that determine the generation of residential waste.

## 2. Methodology

The research was carried out in Mexicali, capital city of the state of Baja California located in the northwest part of Mexico. According to the II Population and Housing count 2005, Mexicali has a population of 855,962, which represents 30% of the state's population.

Mexicali's weather is arid-dry with scarce annual rain; its location on the Tropic of Cancer makes this region a place with extreme climate. This municipality is characterized by its agricultural, industrial and tourist activities; prominent are those activities of the tertiary sector (commerce, services and tourism) that provides employment to about 52% of the population.

In order to carry out this research, we assessed the waste generated by households of a community in Mexicali; for such purpose, a study on the generation and quantification of waste through sampling was conducted. Waste sampling was carried out in three stages corresponding to three different years. A survey was also conducted to obtain demographic data of the population under study. For the development of this research work, data from the three stages of the original research study were assessed and taken as a starting point.

After analyzing the data stored in the database of the original project, the required information was generated so as to characterize the community's residential solid waste (RSW) in the three stages, establishing weight, composition, consumption habits, number of children, educational level, family income, and number of residents per house.

The results obtained from the database were interpreted to identify the study variables and the mathematical model to be used, so as to try and implement such model in the planning, reduction and transport of RSW.

In this stage, the level of correlation with the data generated from the three sampling processes was assessed. It is worth mentioning that the sampling carried out in each stage was different: the sample included 53 households in the first stage; in the second stage, 52 households; and in the third one, 76 households.

The community that this research covered does not reflect a representative sample of the city's population; it only reflects the behavior of three neighborhoods, each representing a defined socio-economic stratum. For the waste generation analysis, the annual seasonal variations were not considered.

### 2.1. Predictor variables to be included in modeling

The behavior of RSW generation is impossible to explain by using a single predictor variable. Thus, to find the mathematical