**Article** **Journal-Urban-Rural and Regional Economy**
December, 2023 Vol.4 No.13 25-34

# Study of the dynamics of urban solid waste management considering the characterization of the collection routes in the municipality of Huatusco, Veracruz

# Estudio de la dinámica de la gestión de residuos sólidos urbanos considerando la caracterización de las rutas de recolección en el municipio de Huatusco, Veracruz

ESPINOZA-CORTES, Claudia Sofía†, SOLIS-JIMENEZ, Miguel Ángel*, CALDERÓN-PALOMARES, Luis Antonio and TEJEDA GARCIA, Rafael

*Tecnológico Nacional de México - Instituto Tecnológico Superior de Huatusco. Av. 25 Poniente No. 100 Colonia Reserva Territorial, Huatusco. Ver. CP. 94106*

ID 1st Author: *Claudia Sofía, Espinoza-Cortes*

ID 1st Co-author: *Miguel Ángel, Solís-Jiménez* / **ORC ID:** 0000-0002-8125-0989, **CVU CONAHCYT ID:** 94216

ID 2nd Co-author: *Luis Antonio, Calderón-Palomares* / **ORC ID:** 0000-0001-9846-5567, **Researcher ID Thomson:** N-6259-2018, **CVU CONAHCYT ID:** 238274

ID 3rd Co-author: **ORC ID:** 0009-0003-7994-8055, **CVU CONAHCYT ID:** 998663

**DOI**: 10.35429/JURRE.2023.13.7.25.34 Received July 11, 2023; Accepted December 30, 2023

Abstract

This study was conducted in the municipality of Huatusco de Chicuellar, in the state of Veracruz, to characterize the urban solid waste collection system, and to identify the pertinent logistical indicators to propose and analyze possible strategies that contribute to the redesign of the current collection system. For the development of the study, sampling was carried out to identify the micro waste collection routes with the help of technological tools such as the Global Positioning System, known as GPS, and they were represented graphically on the Google Earth platform. Through the evaluation of the collection routes, the main logistical indicators were identified, such as the mileage traveled on the routes, diesel consumption and the cost of final waste disposal. The information obtained in the characterization of the routes, in addition to other data obtained in previous studies of MSW generation and composition, carried out in the city, made it possible to develop a dynamic model with which it is possible to present an improvement scenario that consists of separating waste at the source (in families) and to observe the economic impact that this action can have for the municipality.

**Municipal Solid Waste Management, System Dynamics**

**Resumen**

El presente estudio se realizó en el municipio de Huatusco, perteneciente al estado de Veracruz, con el objetivo de caracterizar el sistema de recolección de residuos sólidos urbanos, para identificar los indicadores logísticos pertinentes a fin de plantear y analizar posibles estrategias que contribuyan al rediseño del sistema de recolección actual. Para el desarrollo del estudio, se efectuó un muestreo para identificar las micro rutas de recolección de residuos con la ayuda de herramientas tecnológicas como el Sistema de Posicionamiento Global (GPS) y se representaron de manera gráfica en la plataforma Google Earth. Mediante la evaluación de las rutas de recolección se logró identificar los principales indicadores logísticos como, el kilometraje que se recorre en las rutas, el consumo de diésel y el costo que representa la disposición final de los residuos. La información obtenida en la caracterización de las rutas, además de otros datos obtenidos en estudios previos de generación y composición de RSU realizados en la ciudad, permitieron desarrollar un modelo dinámico con el que es posible presentar escenarios de mejora que consiste en la separación de los residuos desde el origen (en las familias) y observar el impacto económico que dicha acción puede tener para el municipio.

**Gestión de Residuos Sólidos Urbanos, Dinámica de Sistemas**

**Citation:** ESPINOZA-CORTES, Claudia Sofía, SOLIS-JIMENEZ, Miguel Ángel, CALDERÓN-PALOMARES, Luis Antonio and TEJEDA GARCIA, Rafael. Study of the dynamics of urban solid waste management considering the characterization of the collection routes in the municipality of Huatusco, Veracruz. Journal-Urban-Rural and Regional Economy. 2023. 7-13:25-34.

† Researcher contributing as first author.

## Introduction

Municipal solid waste (MSW) management is a sensitive issue for the authorities in charge of its management, as it represents an indispensable service for the population given its repercussions on public health, the environment and the economy. The complexity of the system stems from the social, economic, technological and environmental implications related to it (ECLAC.

Since the 1990s, the Ministry of Environment and Natural Resources (2009) of the Federal Government has recognised that Mexico faces great challenges in the integrated management of solid waste, due to:

- High costs associated with the operation of public waste management systems.
- Lack of knowledge on the part of waste managers
- Lack of interest on the part of citizens
- Increase in solid waste production rates
- Excessive consumption
- Reduction of the useful life of products, among others.

It has been observed in different research studies that the process with the highest incidence and that presents the greatest complications at the time of implementation is the collection routes, the most neglected factors being the frequency with which the collection truck passes and the scheduling of timetables for each zone, as well as the concern in the municipalities about the insufficient fleet of collection vehicles and high operating costs.

In most of the methodologies related to the analysis of household solid waste collection routes, the concept of costs is emphasised, taking as a reference that the collection process represents between 70% and 85% of the total maintenance costs of the system, highlighting the need to optimise the process in order to reduce costs.

For authors such as Medina (1999):

The issue of solid waste is of great interest and concern for authorities, institutions and the community, due to the threat it represents to human health and the environment, specifically in relation to the aesthetic deterioration of urban centres and the natural landscape, as well as the proliferation of disease transmitting vectors and the effect on biodiversity.

Among the most relevant points found in research dedicated to the optimisation of routes, the following concepts stand out:

- Topography
- Roads
- Type of population
- Number of inhabitants
- Commerce, schools
- Quantity and type of waste

These are directly related to the equipment and conditions available to operate the collection system.

*Municipal Solid Waste Management*

Currently, "Municipal Solid Waste (MSW) Management" is understood as the set of operations aimed at giving the MSW generated in a given area the most appropriate overall treatment, from the technical, economic, environmental and sanitary points of view, in accordance with its characteristics and available resources (Márquez Benavides, 2011).

*Integrated Solid Waste Management System*

Solid waste management can be considered a management system based on a sustainable approach that has as its primary objective the reduction of waste sent to final disposal, in order to minimise the negative impact of waste and the costs associated with it. The handling or management of each of the phases from waste disposal to disintegration is observed in four stages:

ISSN-On Line: 2524-2083


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- Generation
- Collection and transport
- Transfer
- Final disposal and/or treatment

*Collection*

This is a public service comprising the collection of MSW at the site where it is produced and its transfer to the site where it is treated or disposed of. Collection is differentiated as follows:

- General: without discriminating between different types of waste.
- Differentiated: discriminating by type of waste according to its subsequent treatment and valuation.

*Collection routes*

In the SEDESOL Technical Manual on the generation, collection and transfer of municipal solid waste, routes are defined as the specific routes that collection vehicles must follow on a daily basis in the areas of the locality where they have been assigned in order to collect the waste generated by the inhabitants of that sector in the best possible way.

Waste collection routes in the municipality of Huatusco, Veracruz have usually been designed in an intuitive way by the people in charge of the public cleaning service, and when the government changes there is confusion on the part of the new people in charge, so they do not evaluate the system and operate it in a conventional way, without taking into consideration important aspects such as route modelling and its optimisation through engineering tools that allow for a more efficient performance.

*Basic rules for the design of collection routes*

- Increase the productive distance relative to the total distance.
- Routes should not fragment or overlap.
- The start of a route should be close to the place where the collection truck will be stored and the end close to the place of final disposal of solid waste.
- In places with steep slopes or high gradients, try to make the route from the top to the bottom.
- Try to collect simultaneously from both sides of the street.
- Respect the direction of traffic.
- Avoid left turns and U-turns.
- It is necessary to recognise the characteristics of the city very well so that the routes of the collection trucks do not cause different types of problems.

In this paper, entitled "Characterisation of MSW collection routes and proposal for improvement under the Eco-Driving concept in Huatusco, Veracruz", the aim is to analyse the current MSW collection system in the city of Huatusco, Veracruz, based on data from real routes obtained by means of global geopositioning devices (GPS); with the aim of evaluating the MSW collection routes by means of logistical indicators, in order to propose and analyse strategies that contribute to the redesign of the current collection system.

This project is carried out with the aim of implementing the GPS global positioning system in the collection units to control and monitor the collection routes used by the municipality's public cleaning system, as this system provides tools to identify geographically on a map the points travelled by the units, as well as visualising important information for correct decision making.

In addition, the analysis of the information allows the identification of possible areas for improvement in the public cleaning system, optimising processes and contributing to the sustainable development of the city. By analysing this situation, the aim is to understand the operation of the current routes in order to find opportunities for improvement.

*Macro routes*

The Mexican Ministry of Sustainable Development (SDS), in its manual on integrated solid waste management, calls macro routes the stratification of the city through sectors of operation, for which it establishes the optimal number of trucks, assigning them to fulfil the route according to their operational sector.

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*Micro routes*

A specific route that collection vehicles must follow daily in the areas of the city where they have been assigned, in order to collect the solid waste generated by the inhabitants of the area in the best possible way (Bravo Figueroa, 2021).

*System dynamics*

System Dynamics is understood, in the sense of Forrester (1968), as a methodology for understanding change, using finite difference equations or differential equations. Given the representation of these processes, we can study the dynamics of the set of states available to the system, which is the central theme of the modelling (García, 2017).

**Methodology to be developed**

The Methodology section describes the steps to be followed to carry out the research process, it is divided into three parts: cabinet work, field work and study method.

*Desk work*

- Elaborate the relevant documents to request permission from the Huatusco City Council to carry out the development of the project in coordination with the Municipal Public Services Department, to finally be channelled to the Coordination of Public Cleaning Services, who are directly in charge of the subject in question.
- Hold a meeting with the person in charge of the Coordination of Public Cleaning Services to draw up the planning of the activities to be carried out and to define the dates on which the sampling will be carried out with the GPS devices duly installed.
- Schedule periodic consultations to review the progress of the project and make recommendations to improve the structure of the research work.

*Field work*

- Verify the type and quantity of mobile units in charge of waste collection and check the route map (if available) or the records related to the operation and maintenance costs of the system.
- Determine the carrying capacity of the vehicles.
- Configure the GPS correctly for optimum performance during journeys and install them properly in the units.
- Identify collection routes through the digital monitoring platform corresponding to the tracking device.
- Record the collected information in an Excel database.

*Survey method*

- Locate geographically on a map the GPS tracked points using the Google Earth platform.
- Analyse the fulfilment of the micro routes based on the macro routes established by the system.
- To elaborate a report of the operation indicators obtained in the routes.
- Analyse the data in order to detect inefficiencies in the routing system and propose areas for improvement.
- To elaborate improvement proposals considering the optimisation of the system.

**Results**

Route monitoring coverage.

- The waste collection process is carried out continuously throughout the week in the neighbourhoods of the municipal capital, from 6:00 a.m. to 15:00 p.m. on average.
- An evening tour of Avenues 1 and 2, which are the main thoroughfares in the city, was observed, especially to cover the commercial area and primarily the Juárez Market, which is one of the areas with the highest waste production.

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- Tours are made to cover the service to rural communities, this route is carried out on Wednesdays, Fridays and Saturdays.

- Focal points are taken into account or well known as red points which are the areas that are saturated with waste at any time of the day.

*Macro routes currently operating in Huatusco.*

Due to the fact that Huatusco is a city with a large number of neighbourhoods and therefore a large number of inhabitants, collection was divided into large zones. These zones were delimited by the person in charge of the Limpia Púbica system and their compliance was corroborated based on data obtained from GPS devices. For illustrative purposes, the 2-day macro and micro routes are shown below, which best represent the operation of the current collection system.

*Monday*

Table 1 shows the sectorisation carried out to define the macro routes. It can be seen that three routes were defined for Monday.

| Day | Route 1 | Route 2 | Route 3 |
|---|---|---|---|
| Monday | Avenida 2<br>Avenida 4<br>Avenida 6<br>Avenida 2<br>Avenida 4<br>Avenida 6<br>Avenida 8<br>Emiliano Zapata<br>Los Encinos<br>Los Manantiales<br>Praderas de Axol<br>Laguna<br>Autozone<br>Villas la vista<br>Setse 1<br>Setse 2<br>Maná<br>Restaurante | Avenida 1<br>Avenida 3<br>Avenida 5<br>Avenida 7<br>Agustín Chicuellar<br>Ejidal Acatepec<br>Miguel Alemán<br>Reserva Territorial | Puntos rojos<br>Reserva Territorial |

**Table 1** Macro Routes Monday
*Source: Own elaboration*

Figure 1 shows graphically the macro routes mentioned above, the yellow colour represents route 1, while route 2 is identified with green colour, route 3 is marked with purple colour and finally the red area is the area of influence of the red points.


**Figure 1** Monday macro routes
*Source Google Earth*

Figure 2 shows how the Monday routes operate in detail, showing the streets and avenues along which the collection truck travels. It can be seen that they coincide with the established macro routes.

*Friday*

Taking into account the information in Table 2, we can consider the execution of three routes, one for the urban area, another covers a large part of the urban area and an educational institution, the Autonomous University of Chapingo, which is located on the outskirts of the urban area approximately six kilometres from the municipal palace, in addition to the route that covers the needs of the rural area.


**Figure 2** Micro Routes Monday
*Source: Google Earth*

Figure 3 shows the three routes that were proposed for the public cleaning service in the municipality; however, there are also four zones (represented in black) that do not correspond to the data shown in the table, but are covered by the service on Fridays. Figures 4 and 5 show the macro routes in the urban area.

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| Day 1 | Route 1 | Route 2 | Route 3 |
|---|---|---|---|
| Monday | Avenida 2<br>Avenida 4<br>Avenida 6<br>Avenida 8<br>Morelos<br>Húngaros<br>Guillermo Lira<br>Las garzas<br>Calle 20<br>El molino<br>Cruxtitla<br>Beneficio<br>Alamos<br>Gasolinera Alamos<br>Pepe Coffe<br>Las cañadas<br>Chapingo | Avenida 1<br>Avenida 3<br>Avenida 5<br>Avenida 7<br>Ejidal Acatepec<br>Villas la Vista<br>Xocotla<br>Ampliación Constitución<br>2 de Noviembre<br>Gas Huatusco<br>Ferche Gas 2<br>Fraccionamiento San Antonio<br>Olimpo | Puntos rojos<br>Mesa del rancho<br>Refugio |

**Table 2** Macro routes Friday
*Source: Own elaboration*

Figure 3 shows the three routes that were proposed for the public cleaning service in the municipality; however, there are also four zones (represented in black) that do not correspond to the data shown in the table, but are covered by the service on Fridays. Figures 4 and 5 show the macro routes in the urban area.

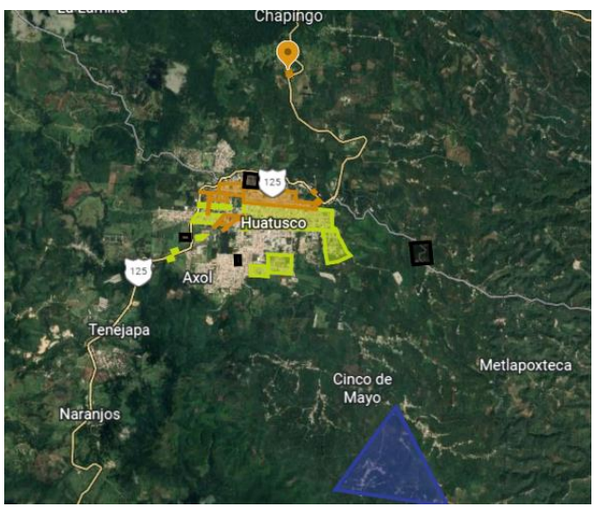


**Figure 3** Macro routes, Friday
*Source: Google Earth*


**Figure 4** Macro routes, Friday
*Source: Google Earth*


**Figura 5** Macro routes, Friday
*Source: Google Earth*

*Red Dot Area*

The red dots referred to in the routes are based on the commercial area because they are areas that many people use as dumps, Table 3 shows the locations of these dots. Figure 6 shows the location of the dots on the digital map.:

| Red dots | Ubication |
|---|---|
| 1 | Corner of 6th Street and 7th Ave. |
| 2 | Corner of 4th St. and 7th Ave. |
| 3 | Corner of 6th St. and 5th Ave. |
| 4 | Corner of 4th St. and 5th Ave. |
| 5 | Corner of 6th St. and 3rd Ave. |
| 6 | Corner of 4th St. and 3rd Ave. |
| 7 | Corner of 2nd St. and 3rd Ave. |

**Table 3** Location of Red Dots in the city


**Figure 6** *Red Dots*
*Source: Google Earth*

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The red box indicates the area of influence of the red dots and clearly shows the points located on the map. This area has such an impact because it is considered a commercial area, the businesses near these points commonly offer organic products, i.e. fruit, vegetables and even flowers. It is known that these types of products are perishable, which is why this area is considered a warning sign because if these sites are neglected, they could become sources of infection, which would have a negative impact on the environment and society. Figure 7 shows the problem mentioned above, these images were taken during the sampling that was carried out.

**Figure 7** Red Dots Urban Area

*Mileage Report*

Table 4 shows the kilometres travelled on each route, as well as the fuel consumption data, based on the distance travelled and taking into account the consumption coefficient: for every 100 kilometres travelled, 38.74 litres of diesel are consumed. This data was taken based on the route to the landfill located in the city of Nogales, in which 142.28 kilometres are travelled and a total of 55 litres of diesel are consumed, giving a performance of approximately 2.581 kilometres per litre. (Consumption data obtained from the Technical Report of the Study of Generation and Composition of Urban Solid Waste in the Municipality of Huatusco, Veracruz).

| Day | Route | Target Name | Kilometres Travelled | Consumption (L) |
|---|---|---|---|---|
| Monday | Route 1 | TK905-54462 | 27.43 | 10.62 |
| | Route 2 | TK905-54486 | 26.38 | 10.22 |
| | Route 3 | TK905-54462 | 42.69 | 16.54 |
| Tuesday | Route 1 | TK905-54462 | 23.68 | 9.174 |
| | Route 2 | TK905-54486 | 39.75 | 15.40 |
| Wednesday | Route 1 | TK905-54462 | 28.83 | 9.23 |
| | Route 2 | TK905-54486 | 21.44 | 8.31 |
| | Route 3 | TK905-54462 | 43.02 | 16.67 |
| Thursday | Route 1 | TK905-54462 | 17.68 | 6.85 |
| | Route 2 | TK905-54486 | 27.96 | 10.83 |
| | Route 3 | TK905-54462 | 31.35 | 12.15 |
| Friday | Route 1 | TK905-54462 | 40.2 | 15.57 |
| | Route 2 | TK905-54486 | 44.1 | 17.09 |
| | Route 3 | TK905-54462 | 158.64 | 61.46 |
| Saturday | Route 1 | TK905-54462 | 24.67 | 9.56 |
| | Route 2 | TK905-54486 | 27.7 | 10.73 |
| | Route 3 | TK905-54462 | 130.67 | 50.63 |
| Sunday | Morning and Evening Route | TK905-54486 | 22.69 | 8.79 |

**Table 4** Mileage of MSW collection vehicles
*Source: Own elaboration*

**Table 4** (Continued) Mileage of MSW collection vehicles
*Source: Own elaboration*

Proposals for improvement

A Forrester model was developed, using the data currently available for the solid waste collection system as input data:

- Kilos collected per kilometre,
- Percentage of recovery,
- Kilometres travelled,
- Tons collected
- Load capacity of the trucks on each trip.

Among the variables to be highlighted is the monthly waste generation in the municipality, which shows a behaviour according to a uniform distribution with a lower limit of 413.05 and an upper limit of 951.81 tonnes, which coincides with the data obtained from the Technical Report of the Study of Generation and Composition of Urban Solid Waste in the Municipality of Huatusco, Veracruz.

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The main elements of the model are the generation per capita, a variable that is introduced by a secondary variable to MSW Generation, this data is complemented with the population of the municipality (59,960 INEGI), the days and the production per capita (0.469 kg/person); in turn, the tons collected are related to MSW because the collection process is based on the efficiency of the system (87.26% of the MSW is collected in the municipality).

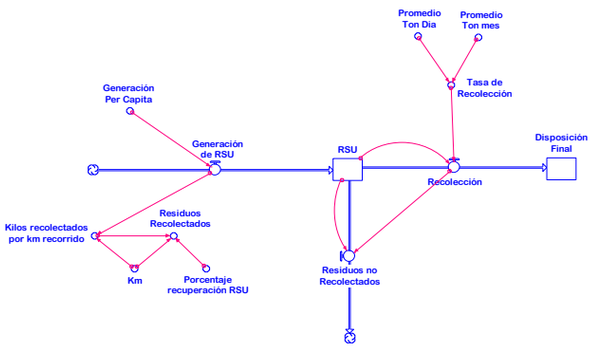


**Figure 8** Dynamic model of the current MSW management system

The model in Figure 8 presents the current operation of the MSW management system in the city of Huatusco de Chicuellar.

The public cleaning service system operates on a daily basis by carrying out mixed waste collection, sweeping the main streets of the city and then disposing of the collected waste in a sanitary landfill. Based on these processes, the modelling of the current situation was constructed as shown in Figure 8, and the data obtained show the behaviour of the system over a year.

Figure 9 shows the amount of MSW generated and collected per month. In the Final Disposal column, there is an approximation of the total number of kilograms of waste to be deposited in a landfill in a year. These data were validated against the information provided by the municipality, so that the behaviour of the model can be considered to replicate what happened in reality.

Sistema Gestión de residuos (Modelo base)

| Months | Generación de RSU | Recolección | Residuos no Recolectados | Disposición Final |
|---|---|---|---|---|
| Jan | 742,440.36 | 564,296.26 | 72,937.28 | 565,607.17 |
| Feb | 856,746.16 | 668,477.05 | 73,963.30 | 1,129,903.43 |
| Mar | 862,461.05 | 753,382.85 | 103,363.31 | 1,798,380.48 |
| Apr | 783,795.76 | 757,425.16 | 105,035.89 | 2,551,763.33 |
| May | 790,910.27 | 693,421.59 | 90,374.17 | 3,309,188.49 |
| Jun | 699,282.77 | 712,241.12 | 78,669.16 | 4,002,610.08 |
| July | 822,238.19 | 614,118.83 | 85,163.94 | 4,714,851.20 |
| Aug | 690,504.21 | 737,881.46 | 84,356.73 | 5,328,970.03 |
| Sep | 707,844.45 | 620,117.68 | 70,386.53 | 6,066,851.48 |
| Oct | 889,201.99 | 617,245.59 | 90,598.86 | 6,686,969.16 |
| Nov | 547,766.60 | 792,471.19 | 96,730.80 | 7,304,214.75 |
| Dec | 905,860.53 | 488,862.90 | 58,903.69 | 8,096,685.94 |

**Figure 9** Results of the current Dynamic Model

The proposal for improvement contemplates the separation of waste at source, i.e. it is analysed what would happen if waste is separated into organic and inorganic waste, considering the different types of waste, as well as the percentages that are being generated in the municipality, so that, with this information, the impact that these actions could have can be seen. The model is presented in three parts due to its size. This can be seen in Figures 10, 11 and 12.

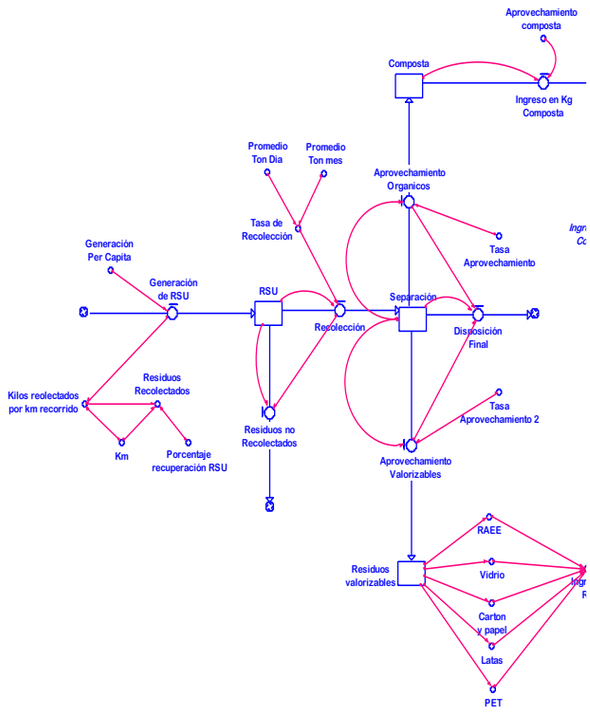


**Figure 10** Dynamic model of the improvement proposal (Part 1)

Some of the results obtained from the improvement model are shown in Figure 13. This figure numerically describes the impact on the final disposal process based on the use of organic and recoverable waste, and by carrying out the corresponding calculations, an approximate reduction of between 40% and 50% can be seen. Positive benefits can be obtained from a differentiated collection, such as the production of compost from organic waste or the sale of recyclable waste such as cardboard, paper, glass, ferrous material, PET, and waste electrical and electronic equipment.

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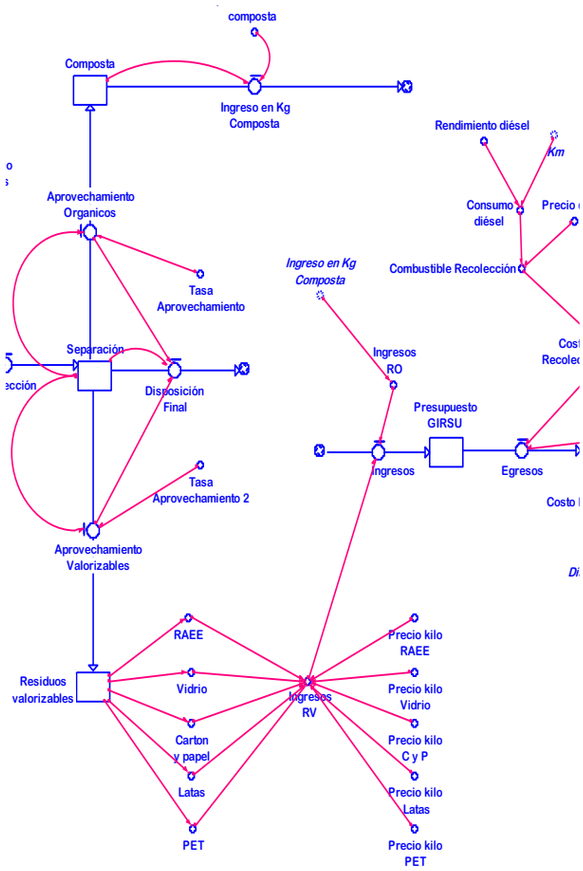


**Figure 11** Dynamic model of the improvement proposal (Part 2)

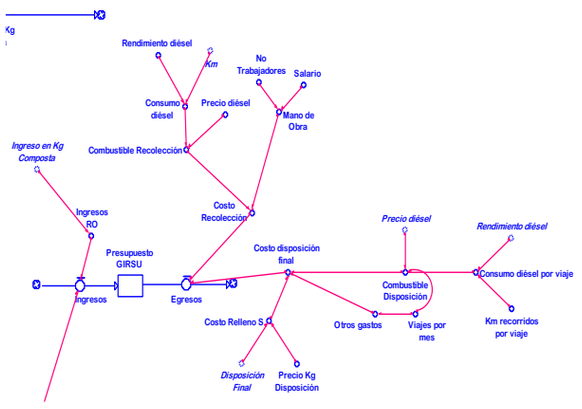


**Figure 10** Dynamic model of the improvement proposal (part 3)

Aprovechamiento residuos orgánicos y valorizables (Disminución en la disposición final)

| Months | Recolección | Aprovechamiento Organicos | Aprovechamiento Valorizables | Disposición Final |
|---|---|---|---|---|
| Jan | 703,040.11 | 219,846.41 | 131,153.54 | 347,740.25 |
| Feb | 600,699.45 | 214,107.29 | 131,960.63 | 356,972.19 |
| Mar | 430,995.24 | 191,940.29 | 112,751.29 | 296,007.88 |
| Apr | 399,480.99 | 142,232.57 | 80,897.81 | 207,864.87 |
| May | 426,559.28 | 140,017.79 | 74,982.58 | 184,480.62 |
| Jun | 430,706.88 | 134,910.36 | 80,065.18 | 211,583.74 |
| July | 424,383.27 | 147,886.94 | 80,843.68 | 201,976.26 |
| Aug | 768,445.53 | 134,079.61 | 79,656.74 | 210,646.92 |
| Sep | 574,615.32 | 254,986.56 | 144,237.23 | 369,221.74 |
| Oct | 824,266.31 | 202,169.94 | 107,855.30 | 264,590.09 |
| Nov | 817,760.06 | 250,244.91 | 154,714.79 | 419,306.61 |
| Dec | 520,244.31 | 282,212.30 | 153,493.56 | 382,054.20 |

**Figure 11** Results of the Dynamic Model of the Improvement Proposal

## Acknowledgement

We thank the mayor of the city of Huatusco, Mr. Ventura Demuner Torres, for the facilities granted through the department of Public Cleaning to obtain the data for the development of the project.

We would also like to thank the Tecnológico Nacional de México as well as the Government of the State of Veracruz who, through the Call 2023: Projects for Scientific Research, Technological Development and Innovation, provided funding for the development of the project.

## Conclusions

From the results achieved in this research in accordance with the objectives set out, it is concluded that obtaining and analysing information is key to assessing the performance of the collection system and adjusting it in a timely manner according to the changing needs of the municipality as it experiences both population and commercial growth.

Therefore, by using this type of GPS device, it is possible to interact with a large number of parameters that are not traditionally considered, such as the effects of traffic on the different roads, the change in the type of vehicles, the mileage on each route that represents the fuel expenditure and, most importantly, the change in the collection method used with all its implications, among others.

A main recommendation is the creation and dissemination of adequate processes and protocols for the disposal and, when necessary, the management of the waste generated, and through this type of strategy, alternatives for the disposal of waste can be offered, such as the creation of deposits for recoverable waste, the creation of programmes that teach the management of compost, among others.

It is recommended for future work to add the economic data of the management system, which will allow for a clearer vision of the impact that can be achieved with the implementation of the suggested policies of waste separation and recovery, entering into a circular economy scheme.

ISSN-On Line: 2524-2083

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