International Joint Conference on Industrial Engineering and Operations Management- ABEPRO-ADINGOR-IISE-AIM-ASEM (IJCIEOM 2020)

Strategy for Solid Waste Collection Optimized with Mathematical Modelling

Rojas J[1], Caballero A[1], Cáceres A[1], Rojas D[2], and Rojas K[2]

Abstract. With the environmental problem gradually aggravating, the correct management of solid waste collection has become relevant within the tasks of the government entities that provide this public service in Peru. However, there are still no improvements given that approximately 30% of garbage is not collected from the streets and more than 50% is not transferred to a landfill [1]. One of the reasons is that the volume of solid waste generated in Peru has increased in the last decade by approximately 38%; nevertheless, another obvious cause is that around 75% of these do not yet have route plans for garbage collection [2]. In a first stage, a clustering model was made based on the composition of the garbage and the volume generated. Then, routing plans were generated for the collection of solid waste using a mathematical optimization model that minimizes the use of resources. For the development of the model, a variant of the Vehicle Routing Problem (VRP) with time windows (VRPTW) was applied, which had as inputs the garbage collection points, which makes up each housing in the sector, and the location of the landfills as final destinations. It is important to consider that the model will be carried out for a particular sector, which is the watering place in the department of La Libertad; however, it is possible to apply to another sector.

Keywords: Solid Waste Collection; Route Modelling; Vehicle Routing Problem Time Windows; Public Services; Clustering.

1 Introduction

During the last decade the population has increased enormously, the city and economic development have resulted in an adverse element to well-being, which is quantified as the generation of solid waste, which has increased considerably. The traditional door-to-door municipal waste collection system has become obsolete, in addition the disposal of waste brings with it problems of segregation, treatment, pollution either in the air (by burning the garbage) or in the water (underground filtration), and greenhouse gas generation. That is why there is a need to optimize the management of solid waste, by reducing the production of solid waste [3]. The Management of Municipal Solid Waste is a challenge faced by developing countries, given that poor management of treatment and disposal methods will directly impact the environment, health and infrastructure of a locality. The participation of government entities (central and provincial), NGOs and private sectors being necessary [4]. However, the social aspect represented by the recyclers must be taken into account. A recycler is mostly an informal worker who is part of the value chain of the solid waste collection, classification and segregation process, to subsequently commercialize urban solid waste (mainly plastic, cardboard, metals and glass). There are cases where recyclers are registered by municipalities, in order to formalize them in the value chain, allowing them to improve the quality of life of these people (generating income and health) [5]. At present, some countries have received in the management of municipal solid waste the operations research techniques, by minimizing costs in the planning of solid waste management. In addition, it is essential to relate it to sustainable management, having as an additional objective the minimization of greenhouse gas emissions, resulting in environmental protection [6].

[1]Jonatán Rojas (e-mail: jrojasp@pucp.pe); Andrea Caballero (e-mail: andrea.caballero@pucp.pe); Alexia Cáceres (e-mail: alexia.caceres@pucp.pe). Pontificia Universidad Católica del Perú, Lima, Perú.

[2]Diana Rojas (e-mail: diana.rojas@pucp.pe); Karen Rojas (e-mail: Incoabsac@hotmail.com). INCOAB, Trujillo, Perú.

In Peru, the Ministry of Environment - MINAM has developed efforts to improve the collection and segregation of municipal solid waste. In 2017 approximately 22, 227.906 tons of solid waste was collected per day [7], where 50.44% of the volume was generated by the departments of Lima and La Libertad. In 2017, MINAN published the regulation of the Law of Integral Management of Solid Waste by Supreme Decree No. 014-2017-MINAM [8], focusing on the population becoming aware of the importance of segregation of solid waste from the source, trying to minimize the generation of waste, reusing and taking advantage of recyclable products using them as inputs for other derived industries. This decree arises as a national concern that only 1.9% of total solid waste is reusable [9]. In the current scenario, the municipalities are the entities responsible for providing support for the collection, transport and treatment of solid waste from their community. Each municipal government independently manages its solid waste collection under the incentives and guidelines of the Ministry of Environment, which is why this research seeks to optimize the coverage of solid waste collection from a district north of the city of Trujillo , the objectives being to increase the coverage of the solid waste segregation plan through the use of mathematical modelling and to train 7% of the population on segregation at the source, in order to have a clean and orderly district which is reflected in community quality of life.

2 State of Art

Operations research is the use of quantitative methods to make decisions by analyzing and improving systems operations. These systems can be of the financial, engineering or industrial type. Operations research establishes the synergy of analytical tools from different disciplines; They are also based on mathematical optimization, which to be developed need computer support, in order to provide information and knowledge of the systems [10].

Decision making is optimal when analysing the system as a whole, that is, when the effects of several parameters are taken into account together. In general, in the abstraction of a problem, the optimal decision is made by developing mathematical models and performing a sensitivity analysis of the different parameters; which represent different environment scenarios [11]. Operations research reached maturity during World War II. It is currently considered a difficult discipline to understand, although it has applications in organizations; among them they are used to model and solve problems of production, logistics, finance, etc. Within the organizations there are multiple decision makers with conflicting goals and objectives, which analyse operations with a high level of uncertainty and aim to reduce costs and increase service quality [12].

One of the main tools of operations research is linear programming. A linear program (LP) is an optimization problem that has linear functions, and has an objective which is to maximize or minimize, and is subject to restrictions (equations or inequalities) [13]. A linear programming problem is defined as follows:

Linear objective function: $maximize\ U = C_1X_1 + C_2X_2 + C_3X_3 + \cdots + C_nX_n$ (1)
Constraints:

$$Subject\ to:$$
$$a_{11}X_1 + a_{12}X_2 + a_{13}X_3 + \cdots + a_{1n}X_n \{\leq, =, \geq\}\, b_1 \quad (2)$$
$$\vdots$$
$$a_{m1}X_1 + a_{m2}X_2 + a_{m3}X_3 + \cdots + a_{mn}X_n \{\leq, =, \geq\}\, b_m \quad (3)$$
$$\forall\, X_i \geq 0; i \in \{1, 2, 3, \dots, m\} \quad (4)$$

2.1 Clustering Model

A cluster model seeks to create groups of entities that share similar attributes within a defined population. One way to assimilate clustering as a mathematical model is to associate a distance between the different points of our population, which represents the similarity between them. Then a clustering function is used, which is any function that, starting from a population N, brings together n entities to form k groups. At the time of segmentation, it should be evidenced that the distance between the points of the same cluster is small, while the distance between points of different clusters is large [14]. Linear and mixed programming can be used as one of the clustering functions. A case of this can be evidenced in the application in customer segmentation, in which the optimal partition of a data of n units in m dimensions was sought, in which the objective function was to minimize the radius of the clusters given the distance and number of clusters desired [15]. In the same way, the binary programming method can be used to solve a problem of location of warehouses, in which there are clients i, which will be segmented according to the warehouse j that will attend them. In this case, the potential places for locating the stores j are taken as predetermined data, and the binary variables Xij are used to determine if the client i was served by the store j, or if it belongs to the cluster that will be served by it, and the binary variables Yj that determine if the warehouse was built at the potential location j; and seeks to minimize the distance to travel. According to Chopra and Meindl [16], a warehouse location optimization model requires the following data:

n = Number of possible locations and capacities of potential stores
m = number of demand points
D_j = demand of point j
K_i = Capacity of the potential warehouse
f_i = Fixed cost of potential warehouse i
c_{ij} = Cost of moving items from warehouse i to point j

Having the following decision variables:
y_i = 1 if the warehouse is installed, 0 if it is closed.
x_{ij} = Amount sent from warehouse i to point j

$$Min = \sum_{i=1}^{n} f_i y_i + \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} x_{ij} \quad (5)$$
$$\sum_{i=1}^{n} x_{ij} = D_j \qquad \forall\, j = 1, \ldots, m \quad (6)$$
$$\sum_{j=1}^{m} x_{ij} \leq K_i y_i \qquad \forall\, i = 1, \ldots, n \quad (7)$$
$$y_i \in \{0; 1\} \qquad \forall\, i = 1, \ldots, n \quad (8)$$
$$x_{ij} \geq 0 \quad (9)$$

2.2 *Routing Model*

The mathematical route design model refers to any problem related to the distribution of goods between deposits and customers. It seeks to determine a set of routes that start and end in a warehouse, so that all customers are served. The objective is to minimize the total distance traveled so that operational restrictions are respected [17]. This model can be represented as a graph that joins arcs and nodes. Each node represents a customer with an assigned demand, and each arc represents a non-negative cost that joins each pair of nodes. The initial node is called no that will represent the deposit.

$$min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij} \quad (10)$$
$$Subject\ to:$$
$$\sum_{j \in V} x_{ij} = 1 \qquad \forall i \in N \quad (11)$$
$$\sum_{i \in V} x_{ij} = 1 \qquad \forall j \in N \quad (12)$$
$$\sum_{i \in V} x_{io} = |k| \quad (13)$$
$$\sum_{i \notin S} \sum_{j \in S} x_{ij} \geq r(S) \qquad \forall S \sqsubseteq N, S \neq \emptyset \quad (14)$$
$$x_{ij} \in \{0,1\} \quad (15)$$

The scientific community has adopted the entire linear programming models to optimize the design of the municipal solid waste management network. The economic and environmental aspects are considered in these types of models. To solve the multi-objective model, the restriction method is often used [17].

Currently, more than 50% of the world's population lives in cities and the urbanization rate is increasing rapidly. This adds challenges in waste management systems at different stages: waste generation, waste collection, waste treatment and disposal, and waste recovery. The waste collection capacity and efficiency of each municipality vary and depend on labour budgets, route design and coverage areas. In the urban solid waste value chain, the informal sector plays an important role in the collection, classification and recovery of recycling waste. Substantial efforts are being made in developing countries to reorient these efforts [18]. Therefore, solid waste management in cities has proved to be a complex task for public policy makers who seek to reduce costs when making decisions. That is why the emphasis of municipalities is focused on the optimization of waste management. This objective can be achieved through the use of operations research tools to locate general and recyclable waste collection sites and create an effective collection route system for trucks thus achieving a reduction in environmental impacts [19].

3 Current Situation

Peru it is estimated that 19,000 tons of solid waste are produced daily, this is equivalent to three full national stadiums [20], of which only 52% of solid waste goes to landfills [21], 44% go to dumps, stay in the street or are thrown into the water and only remaining 4% is reused [22]. In addition to polluting cities, beaches are also being contaminated. In 2019, the Regional Health Management of La Libertad claimed that only three beaches in the region are considered healthy and suitable for bathers [23].

The district of Huanchaco is located in the northwest area of the city of Trujillo, Peru. Of which approximately 96.32% corresponds to housing within the urban area and 3.68% to housing within the rural area.

The population of the district of Huanchaco is 44,806 inhabitants who reside in 12,555 homes grouped in 14 neighbourhood areas that generate a total of 766 tons of waste on average per month. This study will focus on neighbourhood zones 1 and 2 that correspond to the capital of the district. Figure 1 illustrates the map of these neighbourhood areas. In addition, a classification of the waste generated on average by the population of the area was made. We can group it into inorganic reusable solid waste, organic reusable solid waste, and nonreusable solid waste. To determine what types of solid waste should be segregated at the source it is necessary to conduct a characterization study in order to know the physical composition of the solid household waste of the district, then identify and analyse the market demand for each type of solid waste.

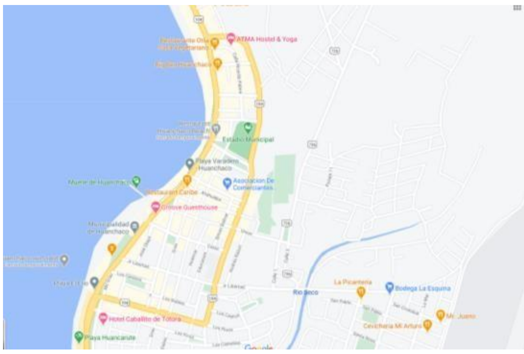

Fig. 1 Map of neighborhood areas 1 and 2.

4 Proposed model

In the search for efficiency when collecting recyclable material, it is not convenient to have mobile units that visit house by house. In this sense, the strategy proposed involves three phases: first, a study of solid waste characterization will be developed to determine its composition and volume, a second one to locate deposits where neighbors will carry recyclable material, and then a third phase where the routing of collection trucks that visit each of these deposits is carried out. Each block will be considered as a node and a demand will be assigned depending on how much solid waste it generates. Each node was located using the Google Earth Pro program as shown in Figure 2. In total 77 nodes were set for this neighborhood and each one has a specific demand assigned, along with its latitude and longitude attributes.

Fig. 2 Map of neighborhood areas 1 and 2 with 77 nodes.

4.1 Characterization

In this phase, a sample of homes was registered to characterize solid waste by type of component and volumetric weight. For this, 120 homes were analyzed for 7 days. In Table 1 the characterization is detailed.

Table 1 Solid Waste Characterization

Types of solid waste	**Average**	**Percentual composition**
1. Organic material	8.87	35.8%
2. Wood, foliage	1.2	4.9%
3. Paper	0.76	3.1%
4. Cardboard	1.31	5.3%
5. Glass	0.59	2.4%
6. PET Plastic	0.43	1.7%
7. Hard plastic	0.35	1.4%
8. Bags	1.6	6.5%
9. Technopor and similar	8.87	35.8%
10. Metal	0.73	2.9%
11. Fabrics, textiles	0.56	2.3%
12. Rubber, leather	0.28	1.1%
13. Batteries	0.33	1.4%
14. Remains of medicine	0.26	1.1%
15. Sanitary waste	2.39	9.7%
16. Inert waste	4.61	18.6%
17. Others	0.22	0.9%
Average volumetric weight		166.98 kg/m^3

4.2 Deposit Location Phase

For this phase, it is proposed to use an optimization model that seeks to minimize the total amount of deposits of recyclable material. In this model, the demand restrictions for each node must be respected, and the capacity that each container of recyclable material could withstand. In addition to this classic model, a restriction of the maximum that a person must travel to leave their waste in the assigned deposit is added. The proposed model for this first phase is presented in Figure 3. The objective function seeks to minimize the number of deposits, while the first restriction limits that the maximum that a person will travel to dispose of their waste is 100 meters. The following restriction ensures that all demand nodes are visited and the last restriction indicates a relationship between the allocation variable X with the decision to have or not have a deposit in a specific node Y.

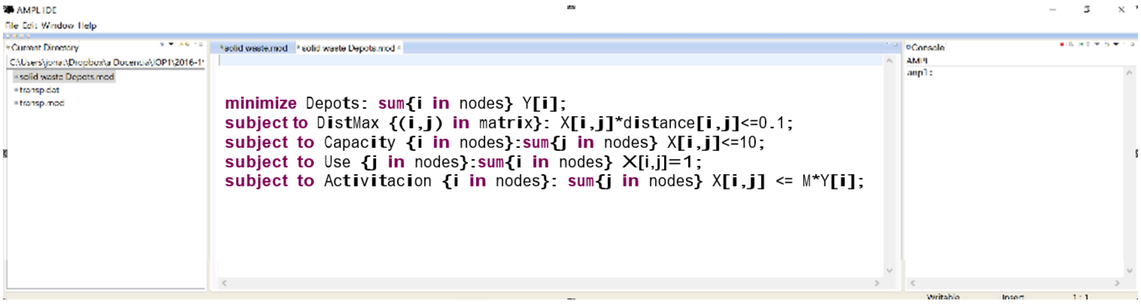

Fig. 3 Location model.

4.3 Routing Vehicles Phase

In this second phase there is already information on where the waste deposits are located and it is proposed to use a routing model for the collection of recyclable material from these deposits, starting and finishing the route at the base located in the district of El Milagro, as shown in Figure 4.

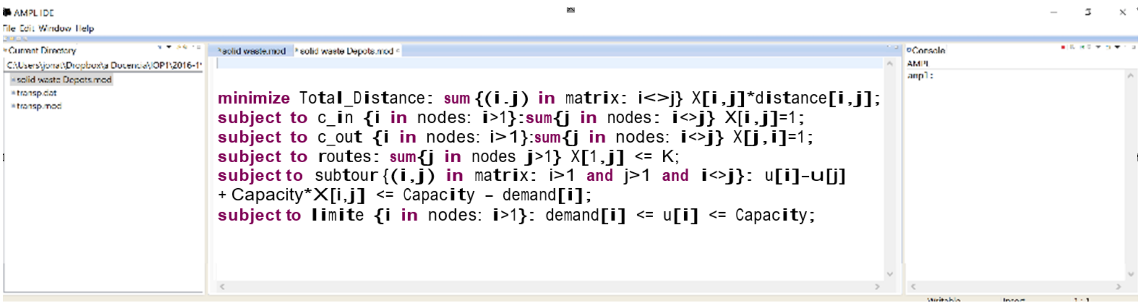

Fig. 4 Vehicle routing models.

5 Results

For the execution of the proposed model, the AMPL optimization program was used in its full version. The solver chosen was CPLEX in version 12.6.3.0 on a core i5 laptop with 8 GB of RAM. As described in the first part, the proposed methodology is divided into 2 phases: deposit location and vehicle routing.

The first phase was executed the model described on the parameters mentioned in the previous section. The result was that 16 deposits for recyclable material will be implemented in the nodes. It can be seen that the maximum number of nodes allocated per deposit is 10 and the maximum distance they travel is 0.1

kilometers. These 16 selected nodes will serve as input data for the next vehicle routing model. With this information a distance matrix will be calculated and the demand captured by this neighborhood waste container will be assigned. A starting point is added to the model, which is where all the recyclable material from the studied community called "Dep" is collected. This research proposes a methodology applied in the district of Huanchaco, Trujillo, obtaining 16 deposits of potentially recyclable waste. Each of these deposits will have a demand that considers 0.57 kilograms per inhabitant per day.

In the second phase of the study, a circuit was designed for each deposit so that the waste collector can take the total generated in the week to the base in the district of El Milagro. The main advantage of the proposal is that it has a methodology replicable to other urban areas of Trujillo, including other departments of Peru. The necessary information is an estimate of the generation of solid waste per block and the capacity of the collection fleet.

Optimizing the use of municipal resources leads to an improvement in the coverage service in garbage collection, generating an increase of 14.75% in the population's satisfaction with the perception of basic services (internal municipal survey on solid waste management).

6 Conclusions

This research was developed in the Huanchaco district, with a pilot sample of 7% of the population, through the study of Characterization, Segregation, and Management of Solid Waste. The number of garbage collection containers and the route associated with its collection through trucks were determined. The routes obtained are shown below:

$$Route\ 1: Dep - C_6 - C_1 - C_9 - Dep$$
$$Route\ 2: Dep - C_{31} - C_{16} - Dep$$
$$Route\ 3: Dep - C_{34} - C_{38} - C_{40} - Dep$$
$$Route\ 4: Dep - C_{50} - C_{51} - C_{61} - Dep$$
$$Route\ 5: Dep - C_{68} - C_{65} - C_{74} - Dep$$
$$Route\ 6: Dep - C_{76} - C_{26} - Dep$$

The linear programming model developed, and the support software is flexible and scalable, that is, in the next phase of the solid waste segregation study, it can be applied to the entire district, since there is mathematical and technical feasibility. However, although local governments have their budget for these activities, the municipality has a late response in these projects; It remains as an alternative to be subject to the funds provided by the Ministry of the Environment – MINAM.

7 References

1. Ministerio del Ambiente del Perú (2018). Nueva ley y reglamento de residuos sólidos. Last accessed September 16th, 2019.
2. EPG Universidad Continental (2019). ¿Cómo se manejan los residuos sólidos en el Perú? Last accessed September 24th, 2019.
3. Yousefloo, A. & Babazadeh, R. (2019). Designing an Integrated Municipal Solid Waste Management Network: A case study. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2019.118824
4. Iyamu, H., Anda, M. & Ho, G. (2020). A review of municipal solid waste management in the BRIC and high-income countries: A thematic framework for low-income countries. Habitat International 95 (2020) 102097.
5. Fidelisa, R., Marco-Ferreira, A., Antunes, L. & Komatsuc, A. (2020). Socio-productive inclusion of scavengers in municipal solid waste management in Brazil: Practices, paradigms and future prospects. Resources, Conservation & Recycling 154 (2020) 104594.
6. Mohsenizadeh, M., Kemal, M. & Kentel, E. (2020). Municipal solid waste management with cost minimization and emission control objectives: A case study of Ankara. Sustainable Cities and Society.
7. INEI (2018). Cantidad promedio diaria de residuos sólidos (basura) recolectada, según departamento, 2017.

https://www.inei.gob.pe/estadisticas/indice-tematico/c-residuos-10291/

8. MINAM (2017). NORMAS LEGALES - Decreto Legislativo N° 1278, Decreto Legislativo que aprueba la Ley de Gestión Integral de Residuos Sólidos. Decreto Supremo N° 014- 2017-MINAM. http://www.minam.gob.pe/disposiciones/decreto-supremo-n-014-2017- minam/
9. MINAM (2018). En el Perú solo se recicla el 1.9% del total de residuos sólidos reaprovechables.
10. Carter, M., Price, C. and Rabadi, G. (2019). Operations Research: A Practical Introduction. 2019 by Taylor & Francis Group, LLC.
11. Tripathy, A., Subudhi, R., Patnaik, S., and Nayak, J. (2019). Operations Research in Development Sector. https://doi.org/10.1007/978-981-13-1954-9
12. Kahraman, C. & Topcu, Y. (2018). Operations Research Applications in Health Care Management. https://doi.org/10.1007/978-3-319-65455-3
13. Cottle, R. & Thapa, M. (2017). Linear and Nonlinear Optimization. International Series in Operations Research & Management Science. Springer. https://doi.org/10.1007%2F978-1- 4939-7055-1
14. Kleinberg, J. (2002). An impossibility theorem for clustering.
15. Sağlam, B., Salman, S., and Türkay, M. (2006). A mixed-integer programming approach to the clustering problem with an application in customer segmentation.
16. Chopra, S., & Meindl, P. (2016) Supply Chain Management: Strategy, Planning, and Operation. Pearson Education.
17. Dantzig, G. B., & Ramser, J. H. (1959). The truck dispatching problem. Management science, 6(1), 80-91.
18. Pharino, C. (2017). Challenges for Sustainable Solid Waste Management Lessons from Thailand. Springer Nature Singapore.
19. Gilardino, A., Rojas, J., Mattos, H., Larrea, G. and Vázquez, I. (2017). Combining opera- tional research and Life Cycle Assessment to optimize municipal solid waste collection in a district in Lima.
20. RPP (2019). Conoce cómo clasificar tu basura para reciclar. https://rpp.pe/peru/actualidad/como-debo-clasificar-mi-basura-para-reciclar-noticia- 1235374
21. RPP (2019). ¿Dónde acaba la basura que botas? https://rpp.pe/peru/actualidad/donde- acaba-la-basura-que-botas-ciudades-con-futuro-noticia-1235619?ref=rpp
22. La República (2019). El 50% de la basura de los hogares es orgánica y reutilizable ¿Cómo aprovecharla?
23. La Industria (2019). ¡Cuidado! Solo tres playas están aptas para bañistas en La Libertad. http://www.laindustria.pe/nota/12716-cuidado-solo-tres-playas-estn-aptas-para-baistas-en- la-libertad