UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

Reverse logistics analysis to evaluate the waste management in the Galapagos islands

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Trabajo de fin de carrera presentado como requisito para la obtención del título de
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RESUMEN

Las islas Galápagos, conocidas como las islas encantadas, son uno de los lugares con mayor biodiversidad del planeta; como resultado, fueron declaradas Patrimonio Natural de la Humanidad en 1978 por la UNESCO (Ecogal S.A., n.d.). En las últimas décadas, la densidad de población ha aumentado notablemente, lo que origina contaminación y la generación de altas toneladas de desechos. Por lo tanto, su gestión de residuos se ha convertido en una condición crítica para ser analizada para su conservación, especialmente debido a la falta de políticas e infraestructura adecuadas para manejar dicho problema. Debido a que el transporte en la gestión de residuos es relevante, es necesario identificar rutas óptimas para el transporte de residuos, y a lo largo de las Islas Galápagos no es una exención. Por lo tanto, se estudiará una metodología que incluya la recolección, análisis y validación de datos existentes considerando la frecuencia y el volumen de la gestión de residuos. Como resultado, se obtendrá un modelo matemático que optimiza estas rutas, con el objetivo de reducir todos los costos asociados con el transporte de los desechos.

Palabras clave: Islas Galápagos, gestión de residuos, optimización, rutas, AMPL.

ABSTRACT

The Galapagos islands, known as the enchanted islands, are one of the most biodiverse places on the planet; as a result, they were declared natural Heritage of Humanity in 1978 by UNESCO (Ecogal S.A., n.d.). In the last few decades, the population density has noticeable increased, which originates pollution and the generation of high tons of waste. Therefore, their waste management has become a critical condition to be analyzed for their conservation, especially because there is a lack of adequate policies and infrastructure to handle such problem. Due that the transportation in waste management is relevant, it is necessary to identify optimal routes for the waste's transportation, and along the Galapagos Islands is not an exemption. Therefore, a methodology that includes the collection, analysis, and validation of existing data considering the frequency and volume of the waste management will be studied. As a result, a mathematical model that optimize these routes will be obtained, with the aim to reduce all the costs associated to the waste's transportation.

Keywords: *Galapagos islands, waste management, optimization, routes, AMPL.*

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1. Introduction

The Galapagos islands were declared Natural Heritage of Humanity in 1978 (Ecogal S.A., n.d.), and they constitute an archipelago located 600 miles off the coast of the continental Ecuador (Mancero, J., 2018). Well-known of their unique biodiversity, they are currently vulnerable due to the pollution and an improper resource utilization. As Tuci, Re and Rizzi (2014) mention, the rapid growth of the population, together with the lack of inadequate policies and infrastructure, leads to the inevitable increase in anthropic damage to natural resources. Being the anthropic damage, the one caused by the human being, such as deforestation and ground contamination because of plastics.

Although the archipelago has over 20 islands (Galapagos Conservancy, Inc., n.d.), only five of them are inhabited, being these: Santa Cruz, San Cristobal, Isabela, Floreana and Baltra islands (WWF & Toyota, 2010). However, Baltra is not considered as a separate entity, but as part of Santa Cruz (GAD Santa Cruz, 2019) because the closest airport to enter to Santa Cruz island is located in Baltra (See Figure 1). Even though these islands are very crowded, with a population of 25.244 people (INEC, 2016), a poorly waste management treatment has been carried out during the years. Since for waste management, transportation is necessary, an optimum handling of these activities must be analyzed because of the difficulty of freight movement and the return of waste to the continent. Furthermore, this situation becomes even more complex because not the 100% of rural and urban zones have coverage of waste collection (Dirección del Parque Nacional Galápagos, 2014). All of these problems, have gained importance in recent years, making it necessary to execute a study that includes a proposal of a mathematical model to evaluate the maritime and land movement of waste inter islands and to the continent.

Figure 1. Map of available airports in Galapagos (Jardín de Helena, n.d.).

2. Objective

Identify route options for waste transportation from the Galapagos islands to the continental Ecuador considering its frequency and volume, by the collection, analysis and validation of the existing data, for a creation of a mathematical model that optimizes those routes.

3. Literature review

This study involves an analysis of the current situation in Galapagos and their waste management, with the purpose to map the process being held in reality and identify the main areas that need to be optimized. Therefore, relevant topics must be studied.

3.1.Situation Analysis in Galapagos

3.1.1. Urbanization

From the last census of 2015, the Galapagos islands had a population of 25.244 people with an increment of 9,5% in the last five years (INEC, 2016). Although, about the 3,3% of the territory is habitable and the other 96,7% is protected area (Ragazzi et al., 2014), it has a population density of 105 people per Km^2 (Lozano, 2018). Some relevant data of the inhabited islands are presented in Table 1.

Table 1. Inhabited islands and their most important facts.

Island	**Surface (km^2)**	**Waste generated**	**Population**
Santa Cruz	986 (Galapagos Conservancy, n.d.)	14,35 ton/day (GAD Santa Cruz, 2019)	15701 (Delgado, B., 2018)
San Cristobal	557 (Galapagos Conservancy, n.d.)	6,41 ton/day (GAD San Cristóbal, 2019)	7088 (Delgado, B., 2018)
Isabela	4670 (Galapagos Conservancy, n.d.)	1,43 ton/day (De la Torre, 2008)	2344 (Delgado, B., 2018)
Floreana	173 (Galapagos Conservancy, n.d.)	62,04 Kg/day (WWF & Toyota, 2010)	111 (Delgado, B., 2018)

By a comparison analysis of Santa Cruz island and other places such as China or India, Santa Cruz, shows values from 400 to 500 people per hectare meanwhile in China and India those values reach 367 and 389 respectively (Lozano, 2018), which shows that the island is taking more waste generation than what it can cover.

On the other hand, the main ports of the islands are Puerto Ayora, Puerto Baquerizo Moreno, Puerto Villamil and Puerto Velasco Ibarra respectively (Consejo de Gobierno del Régimen Especial de Galápagos, 2016). These are the docks from where the containers have to be picked up by the vessel for transportation to the continent, reason why they form part of the maritime cost for the mathematical model. Figure 2 shows the aforementioned ports of the inhabited islands in the Galapagos.

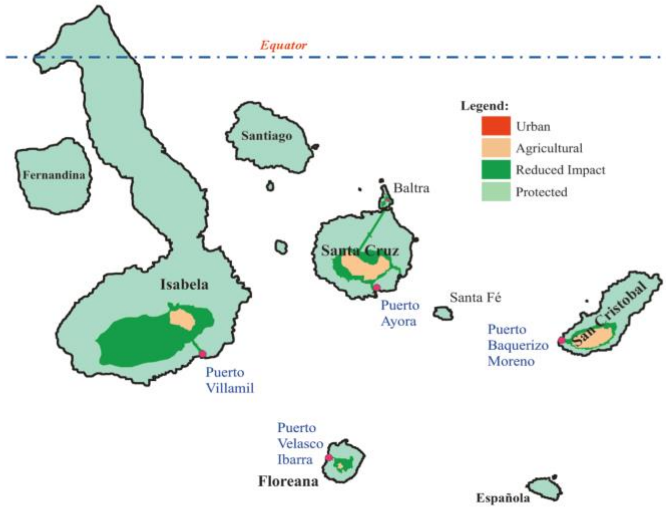

Figure 2. Map of the inhabited islands and their ports (Galeodan, 2012).

3.1.2. Regulatory entities in charge of waste management in the Galapagos

Table 2. Authorities in charge of waste management in the Archipelago.

Authority	Regulation	Source
Autoridad Ambiental Nacional	Recyclables transported to continent have to be delivered to authorized waste managers.	(Decreto Ejecutivo 1363., 2017)
Parque Nacional Galápagos	Movement of waste has to be done according to specific parameters.	(Decreto Ejecutivo 1363., 2017).
Gobierno del Régimen Especial de Galápagos	Use of plastics and control of them.	(Consejo de Gobierno del Régimen Especial de Galápagos, 2018).

Municipalities of each island	General management of solid waste and its movement.	(Del Régimen Especial, Galápagos., 2002).
Ministerio del Ambiente	Waste in Ecuador and routes for waste collection	(Subsecretaría de Calidad Ambiental, n.d).

3.1.3. Solid waste management

Although, all the information presented in this section is outdated, the most recent information dates back to 2014 and it have been used in the study. However, it can be stated that waste is handled differently on each island and that both Appendix A and Appendix B generally show the process carried out by San Cristobal and Santa Cruz, respectively.

In San Cristobal, for example, recyclable materials include a greater number of items, such as aluminum, cans, electronics, glass, paper, plastic, scrap, tetra pack and tires. Similarly, the reject materials are no longer compacted to be taken to the sanitary landfill; and there is a new type of classification called 'hazardous waste' in the program.

Regarding Santa Cruz, hospital waste is no longer incinerated, as this was never really approved by the competent authorities, but rather disposed of in the sanitary landfill. Another update of this process includes that the recyclable materials are the ones actually sold to several companies in Guayaquil.

From the waste collected in San Cristobal, Santa Cruz, Isabela and Floreana islands, 50% of them is recyclable approximately. These waste are classified and they are categorized on those that can remain in the archipelago for reuse and those that should be sent to continent by vessel (Alarcón, 2019). The materials selected for shipment are glass, paperboard, paper, plastic, scrap, cement bags and tires (Escarabay, 2011). There are selected companies that have agreements with the government of San Cristobal and Santa Cruz distinctively for the recycling of the arriving waste (see Table 3).

Table 3. Authorized companies for receiving recycling waste in Guayaquil.

San Cristóbal (O. Palma, personal communication, February 26, 2020).		**Santa Cruz (A. Zhunaula, personal communication, February 28, 2020).**	
Company	*Type of recyclable*	*Company*	*Type of recyclable*
General Tires	Out of use tires	Fibras Nacionales	Paper and paperboard
REPAPERS	Plastic	Reciplásticos	Plastic-PET
CARTOPEL	Paperboard	Tetra Pak	Tetra Pak
CRIDESA	Glass	Holcim	Cement bags
Novacero	Scrap steel	Novacero	Scrap steel
		CRIDESA	Glass

In the Organic law of Special Regime of the province of Galapagos it is stipulated that maritime companies who realize cabotage of merchandise in the coastal area, i.e. maritime transport, from Galapagos, must transport for free the inorganic marketable waste generated in the archipelago, at least three times per year with minimum load percentage (Segundo Suplemento, 2015). However, the stipulated volume is $35m^3$, this being the equivalent of 1 container. It is evident that the volume is insufficient to carry the waste generated by the different islands.

3.1.4. Solid waste generation

The weight of each type of waste generated monthly in kilograms (kg) in the islands is shown in Appendix C. Appendix D includes a database with the collection of several news about specific dates of transportation of waste from Galapagos to Guayaquil. The waste generated per island in kg of the different types of recyclables is shown in Appendix E.

3.1.5. Solid waste collection

In the inhabited islands, waste collection is done in a differentiated manner, following three different categories: rejection, recyclable and organic (O. Palma, personal communication, February 26, 2020). In San Cristobal, waste collection has four different routes: solid household waste, where the collection is done house-to-house; paperboard collection, of the shopping area; street sweeping; and dangerous waste from hospitals. Appendix F has a table of the different days in which each type of waste is collected; additionally, Appendix G shows the collection route of San Cristobal. For waste collection in this island two small trucks are used with a capacity of 2 tons and 1.5 tons respectively, and a big truck with capacity for 4 tons (O. Palma, personal communication, February 26, 2020). Appendix H has a picture of the big truck responsible of the waste collection. There are 18 operators distributed for the different routes, each with one driver and two helpers (O. Palma, personal communication, February 26, 2020). The cost for ground transportation for waste collection and transport is of $12.400 per month; additionally, the cost for street sweeping is of $4.283 per month, and the cost for waste management is of $8.504 (GAD San Cristobal, 2019). Appendix I details the different areas for waste collection.

In Santa Cruz, the waste collection is done house-to-house, following the itinerary shown in Appendix J. For solid waste collection, four trucks with wooden boxes with capacity of 1.5 and two compactor trucks with capacity of 4 tons do the job, together with 18 operators for waste collection and 8 people for street sweeping. Appendix K shows a picture of the compactor truck. (A. Zhunaula, personal communication, February 28, 2020). The cost for ground transportation is $12.517 per month. Appendix L details the different areas for waste collection.

For Isabela, no information could be found about ground transportation, because of that the values for the waste generated were calculated according to a percentage. Given that Isabela's population represents 14,93% of Santa Cruz population, all values about waste generation were calculated under that percentage. Likewise, it was assumed that the number of trucks and operators for this island was equal to those available in Santa Cruz. The collection points were taken randomly according to the map and the city streets, taking 20 collection points for the island.

3.1.6. Waste Transportation to Continent

In the case of San Cristobal, the waste transportation to the continent is carried out by a third party, known as accredited local agents, to whom these recyclable wastes are sold. A list of prices according to the recyclable type can be found in Appendix M (O. Palma, personal communication, February 26, 2020). The local agents, who are in charge of the waste transport to Guayaquil are: Galapason and Recynter Galápagos; being the cost they handle for transportation, around $8 per container. (O. Palma, personal communication, February 26, 2020). The bales weight between 360 kg to 400 kg and occupy a volume of $2m^3$ (O. Palma, personal communication, February 26, 2020). The logistics cost for transportation to the continent is $200 per container (O. Palma, personal communication, February 26, 2020). Transportation to continent does not follow an itinerary; on the contrary, it is sent to continent every time the volume of recyclable waste reaches around 20 tons (O. Palma, personal communication, February 26, 2020). The number of vessels available for the transport of waste are two. In this way, the quantity of containers that are sent in each of these vessels are between 3 and 10, being the capacity of these $33m^3$ (O. Palma, personal communication, February 26, 2020).

In Santa Cruz, there are two vessels available as well, the two agents in charge of transport to continent are Transnave and Fusion, with capacity to transport 4 containers and 10 containers, respectively, of solid waste (A. Zhunaula, personal communication, February 28, 2020). The containers are of two sizes; the small one with capacity of 33 m^3 in which 14 bales fit, and a large one with capacity of $67m^3$ that fit 24 bales (A. Zhunaula, personal communication, February 28, 2020). The weight of the bales varies according to the type of recyclable, since the compactors have different dimensions. In Appendix N the weight of the bales can be found; however, the average weight of the bales is between 360 kg and 400 kg (A. Zhunaula, personal communication, February 28, 2020). The cost at which the government sells the recyclable waste is shown in Appendix M, with an additional item of $0,05/cement bag (A. Zhunaula, personal communication, February 28, 2020). Shipments to the continent are handled every 15 days, taking turns between the two available vessels. All shipments are done with full loads of containers (A. Zhunaula, personal communication, February 28, 2020). The route followed by the vessel for waste collection is: Isabela, Santa Cruz, San Cristobal, returning to Guayaquil, as show in Appendix O, where the recycling company in charge collects the waste (A. Zhunaula, personal communication, February 28, 2020).

3.2. Mathematical models used for MSW (Municipal Solid Waste)

There are different models that can be used to represent a waste collection system problem. First in discussion is the mixed integer programming model with two operational strategies: the first one is for employing on board a vessel a waste compacting machine so bins don't have to be transported, and the second is for transporting bins on board a vessel (Miranda et al., 2015). From them, only one can be applied to the case of Galapagos. This is the transporting of waste bins on board the vessel (Miranda et al., 2015), since, the current system in the islands is handled in this way, meaning that the vessels have no compacting machines and no change in the way of handling waste transportation to continent is anticipated in the operational strategy of this system. The model considers the waste collection location, as well as vessels that depart and return to specific ports, helping determining the best collection tours (Miranda et al., 2015). A restriction of the model is that the collection should be done at least once a week and has to be normally distributed (Miranda et al., 2015).

Other approach is the bi-objective insular traveling salesman problem, in which an approximate Pareto-efficiency solution set is sought (Miranda et al., 2018). A bi-objective approach is used because the costs of deposition are incurred by two different agents: public authorities who collect house-by-house and maritime costs for transporting to continent (Miranda et al., 2018).

A different approach is using only the vehicle routing problem (VRP) with a genetic algorithm (GA) (Assaf & Saleh, 2017). The objective focus on the optimal routes that minimize the total distance traveled by trucks, inside each island, to guarantee a minimal use of fuel; therefore, a reduction of costs and pollution (Assaf & Saleh, 2017). Genetic algorithm is commonly implemented in transit systems for finding optimal routes (Assaf & Saleh, 2017).

A last approach is modeling a bi-objective mixed integer linear programming (Arango González et al., 2017). The main objective of this model is to combine a solid waste collection system in a set of islands with an environmental factor (Arango González et al., 2017). Part of this environmental factor are the accumulation of waste in collection points and the variation of it through time (Arango González et al., 2017). This is a bi-objective problem because of the inverse relationship between minimization in transportation use and the environmental impact because of waste accumulation (Arango González et al., 2017). To complete this model a Pareto front is obtained by two methods: weighted sum and epsilon-constraint (Arango González et al., 2017). Since this model takes into account the environmental impact, it analyzes the effect of waste accumulation by deriving the number of coliforms in the generated leachate, resulting liquid from filtering the fluids that come out of solid waste (Arango González et al., 2017).

Table 4 summarizes the models described above, along with the author that uses that model to solve the waste collecting problem. Appendix P includes a list of the constraints used in the model of each author; that is, the restrictions around which the problem has to be solved. Appendix Q shows a list of the parameters used in the models; that is, the information that must be entered the program in order to solve the problem for the actual necessities.

Table 4. Summary of the models found.

Number	Author	Mathematical Model
1	(Miranda et al., 2015)	Mixed integer programing model with structure of a Vehicle Routing Problem, employing multi-objective methodologies.
2	(Miranda et al., 2018)	Bi-objective insular traveling salesman problem.
3	(Assaf & Saleh, 2017)	Vehicle Routing Problem using genetic algorithm.

4	(Arango González et al., 2017)	Bi-objective mixed integer linear programming.

4. Problem description

In 2015, aproximately 324 kg per capita of solid waste were generated annually in the islands (Consejo de Gobierno del Régimen Especial de Galápagos, 2016). Floreana is the island where less quantity of waste is generated per day, with 75 kg (WWF & Toyota, 2010). The projection shows that every 10 years the generation of solid waste doubles in Galapagos, being Santa Cruz the island with most waste generation due to its population and touristic activities, representing a focus of constant pollution (WWF & Toyota, 2010). According to the waste management plan of Galapagos of 2010, only Santa Cruz has a 100% coverage of solid waste collection; nevertheless, only three landfills exist in Galapagos (WWF & Toyota, 2010). Since 2018, a coastal cleaning plan was implemented (Ministerio del Ambiente, 2018); however, this is not a solution to the problem given that solid waste transportation is carried out only every few months. Nowadays, half of the waste collected goes to landfill and the other 50% is moved to the recycling plant (Alarcón, I., 2019). Once there, separation of waste is done to classify those materials which will stay in the island for reuse and which will be send by vessel to Guayaquil (Alarcón, I., 2019). Isabela and San Cristobal have their own recycling plant as well for 6 months and three years now respectively (La Hora, 2012). The leachate, resulting liquid of a percolating process of a fluid through a solid, are treated in an oxidation pool (Alarcón, I., 2019).

However, its necessary to establish alternatives of centralized locations for waste collection in the inhabited islands, remote site cleaning plans, a ground route for the collection in the islands and a maritime route to transport back to continent the waste that could not be treated in the archipelago. The routes of collection require a frequency of maximum 7 days so the waste does not have an inadequate exposure in the environment (Miranda et al., 2015).

5. Methodology

Since the present study seeks to develop a preliminary mathematical model to analyzes the waste transportation from the Galapagos Islands, the methodology to be used is the one proposed by Hillier and Lieberman about operations research problems(OR). Hillier and Lieberman (2015) divide their methodology into the following phases:

1. Define the problem of interest and gather relevant data.

For this phase, meetings were held with researchers in the area and authorities to collect data. An on-site visit was also carried out to ensure that the data collected remains valid. The tools used were: descriptive statistics, for data analysis, with the use of Tableau and the formulation of the AS-IS situation.

2. Formulate a mathematical model to represent the problem.

For this phase, several mathematical models for maritime, island and land transport were studied to find the one that best suits the current situation and the archipelago data. The main tool that was used was operations research, for the formulation of the preliminary mathematical model.

3. Develop a computer-based procedure for deriving solutions to the problem from the model.

For this phase, AMPL software was used for implementation of the model, which uses algebraic programing for solving problems of great complexity. The solver used is knitro, for nonlinear problems.

4. Test the model and refine it as needed.

For this phase, the model implemented in AMPL is modified with additional constraints such as subtour elimination and predecessor and successor restrictions from the TSP (Traveling Salesman Problem), in order to fit the model to the software with the conditions that apply for Galapagos.

5. *Prepare for the ongoing application of the model as prescribed by management and*

6. *Implement.*

Due to the scope of the study, it should be considered that, only until Phase 4 of the proposed methodology will be reached and explained.

6. Application

In this section, the mathematical model proposed to solve the problem under study will be given, in order to find optimal solutions that will help improve the waste management in the islands.

6.1. Parameters and decision variables

In order to develop a mathematical model, first the decision variables have to be established, this will be the optimal answers that will help improve the situation under study. For this problem, those decision variables are formed by the optimal number of trucks and containers needed per week for waste collection, as well they will be set as integers. On the other hand, there are three binary decision variables that consist on the optimal route for waste collection in each island.

Along with the decision variables, sets are needed, which indicate the different places and types of transport and waste under study. Also, parameters have to be established, this being the actual information collected about the problem for the different sets, such as distance matrices, costs, capacities, etc.

Sets

n, k: $set\ of\ nodes\ between\ collection\ points\ C\ in\ San\ Cristobal$

t, l: $set\ of\ nodes\ between\ collection\ points\ F\ in\ Santa\ Cruz$

r, v: $set\ of\ nodes\ between\ collection\ points\ E\ in\ Isabela$

i: $set\ of\ islands\ I$

o: $set\ of containers\ O$

s: $set\ of trucks\ S$

d: $set\ of\ days\ D$

p: $set\ of\ types\ of\ waste\ P$

pp: $set\ of\ types\ of\ recyclable\ waste\ PP$

Parameters

$dist1_{n,k}$: $distance\ matrix\ between\ nodes\ n\ and\ k\ in\ San\ Cristobal$

$dist2_{t,l}$: $distance\ matrix\ between\ nodes\ t\ and\ l\ in\ Santa\ Cruz$

$dist3_{r,v}$: $distance\ matrix\ between\ nodes\ r\ and\ v\ in\ Isabela$

$C2_o$: $capacity\ in\ volume\ of\ each\ type\ of\ container$

$C3_s$: $capacity\ in\ kg\ of\ each\ type\ of\ truck$

T: $average\ capacity\ in\ kg\ for\ the\ bales$

A: $volume\ that\ each\ bale\ occupy$

$Q1_{o,i}$: $quantity\ of\ each\ type\ of\ container\ available\ in\ each\ island$

$Q2_{d,s,i}$: $quantity\ of\ each\ type\ of\ truck\ available\ in\ each\ island\ per\ day$

P_{pp}: $price\ of\ sale\ for\ each\ type\ of\ recyclable\ waste$

$W1_{p,i}$: $quantity\ of\ each\ type\ of\ waste\ collected\ in\ kg\ in\ each\ island$

$W2_{pp,i}$: $quantity\ of\ each\ type\ of\ recyclable\ waste\ collected\ in\ kg\ in\ each\ island$

$DW_{d,p,i}$: $binary, days\ for\ waste\ collection\ of\ each\ type\ of\ waste\ in\ each\ island$

$f1$: $shipment\ cost\ from\ dock\ to\ depot\ by\ container$

$f2$: $shipment\ cost\ per\ km\ between\ collection\ points\ in\ all\ islands$

$f3$: $shipment\ cost\ per\ trip\ from\ last\ collection\ point\ to\ docks$

$f4$: $cost\ per\ week\ for\ workforce\ in\ all\ islands$

Decision variables

$x_{o,i}$: $number\ of\ containers\ needed\ per\ island$

$z_{d,s,i}$: $number\ of\ trucks\ needed\ each\ day\ of\ the\ week\ per\ island$

$u1_{n,k}$: $artificial\ variable\ for\ San\ Cristobal$

$y1_{n,k}$: $binary\ variable\ indicating\ the\ order\ in\ which\ collection\ points\ have\ to\ be\ visited\ in\ San\ Cristobal$

$u2_{t,l}$: $artificial\ variable\ for\ Santa\ Cruz$

$y2_{t,l}$: $binary\ variable\ indicating\ the\ order\ in\ which\ collection\ points\ have\ to\ be\ visited\ in\ Santa\ Cruz$

$u3_{r,v}$: $artificial\ variable\ for\ Isabela$

$y3_{r,v}$: $binary\ variable\ indicating\ the\ order\ in\ which\ collection\ points\ have\ to\ be\ visited\ in\ Isabela$

6.2. Optimization model

$$Min\ cost:$$

$$\sum_{n,k\in C} f2 * dist1_{n,k} * y1_{n,k} + \sum_{t,l\in F} f2 * dist2_{t,l} * y2_{t,l} + \sum_{r,v\in E} f2 * dist3_{r,v} * y3_{r,v}$$
$$+f4 * 3 + \sum_{s\in S}\sum_{i\in I}\sum_{d\in D} Cost_s * z_{d,s,i} + \sum_{o\in O}\sum_{i\in I} f1 * x_{o,i} + \sum_{o\in O}\sum_{i\in I} f3 * x_{o,i}$$
$$+ \sum_{o\in O}\sum_{i\in I} Cost2_o * x_{o,i} - \sum_{pp\in PP}\sum_{i\in I} P_{pp} * W2_{pp,i}$$

(1)

Subject to:

$$\sum_{o\in O} x_{o,i} * C2_o \geq \sum_{pp\in PP} \frac{W2_{p,i}}{T} * A \qquad \forall i \in I \tag{2}$$

$$\sum_{s\in S} z_{d,s,i} * C3_s \geq \sum_{p\in P} DW_{d,p,i} * (W1_{p,i}/7) \qquad \forall i \in I, d \in D \tag{3}$$

$$x_{o,i} \leq Q1_{o,i} \qquad \forall i \in I, o \in O \tag{4}$$

$$\sum_{d\in D} z_{d,s,i} \leq \sum_{d\in D} Q2_{d,s,i} \qquad \forall i \in I, s \in S \tag{5}$$

$$\sum_{o\in O} x_{o,i} \geq 1 \qquad \forall i \in IO \tag{6}$$

$$\sum_{s\in S} z_{d,s,1} \geq 1 \qquad \forall i \in I, d \in D \tag{7}$$

$$\sum_{s\in S} z_{7,s,2} = 0 \qquad \forall i \in I, d \in D \tag{8}$$

$$\sum_{s \in S} z_{d,s,3} \geq 1 \quad \forall i \in I, d \in D \tag{9}$$

$$x_{o,i} \geq 0 \quad \forall o \in O, \forall i \in I \tag{10}$$

$$z_{d,s,i} \geq 0 \quad \forall d \in D, \forall s \in S, \forall i \in I \tag{11}$$

San Cristobal

$$\sum_{n \in C} y1_{n,k} = 1 \quad \forall\, k \in C \tag{12}$$

$$\sum_{k \in C} y1_{n,k} = 1 \quad \forall\, n \in C \tag{13}$$

$$u1_n - u1_k + \left||C|\right| * y1_{n,k} \leq \left||C|\right| - 1 \quad \forall\, n, k \in C, n \neq 1, k \neq 1, n \neq k \tag{14}$$

$$y1_{n,k} \in \{0,1\} \quad \forall n, k \in C, n \neq k \tag{15}$$

$$u1_{n,k} \geq 0 \quad \forall n, k \in C, n \neq k \tag{16}$$

Santa Cruz

$$\sum_{t \in F} y2_{t,l} = 1 \quad \forall\, l \in F \tag{17}$$

$$\sum_{l \in F} y2_{t,l} = 1 \quad \forall\, t \in F \tag{18}$$

$$u2_t - u2_l + \left||F|\right| * y2_{t,l} \leq \left||F|\right| - 1 \quad \forall\, t, l \in F, t \neq 1, l \neq 1, t \neq l \tag{19}$$

$$y2_{t,l} \in \{0,1\} \quad \forall t, l \in F, t \neq l \tag{20}$$

$$u2_{t,l} \geq 0 \quad \forall t, l \in F, t \neq l \tag{21}$$

Isabela

$$\sum_{r\in E} y3_{r,v} = 1 \quad \forall\, v \in E \tag{22}$$

$$\sum_{v\in E} y3_{r,v} = 1 \quad \forall\, r \in E \tag{23}$$

$$u3_r - u3_v + \left||E|\right| * y3_{r,v} \le \left||E|\right| - 1 \quad \forall\, r, v \in E, r \ne 1, v \ne 1, r \ne v \tag{24}$$

$$y3_{r,v} \in \{0,1\} \quad \forall r, v \in E\,, r \ne v \tag{25}$$

$$u3_{r,v} \ge 0 \quad \forall r, v \in E\,, r \ne v \tag{26}$$

Equation (1) is the objective function which minimizes the total costs from waste collection in islands until its delivery in depot, the costs included in this function are the costs per km per the distance matrices between the collection points in each island, then the cost per week for the salary of the 18 operators per island, then a cost associated with opening each truck depending on its capacity and type. Then the maritime cost per container for shipment to continent, followed by the cost of ground transportation per container for movement from the recycling center to the docks, then the cost of opening each type of container depending on its capacity, and at last, the price of sale per each type of recyclable waste is added.

Equation (2) is the constraint for the containers capacity, indicating that the number of containers need the volume to be greater than the total waste accumulated at the dock, for type of waste 1, which is recyclables. In this equation W2 represents the recyclable waste collected in kg, but since the capacity of the containers is in m^3 and waste is shipped in bales, the total recyclable waste collected is divided by the average weight of bales and multiplied by the volume of each bale. Equation (3) is the constraint for the trucks capacity, indicating that the number of trucks need the weight capacity to be greater than the total waste accumulated at the dock per day. For this equation W1 which is the total waste collected per island is divided by seven to obtain the average weight per day collected in each island and then multiplied by DW which indicates the day for collection of each type of waste. Equation (4) constraints the output, so the number of containers is less than or equal to the containers available for each island. Equation (5) is same as constraint four, but for trucks. Equation (6) assures that at least one container will be available for each island. Equation (7) establishes that there has to be at least one truck for each day for island one, which is San Cristobal. Equation (8) establishes that for island 2, which is Santa Cruz, no trucks are needed in day seven, meaning Sunday. Equation (9) is the same as 7, but for Isabela. Equations (10) and (11) are non-negativity constraints for the decision variables z and x.

Equations (12), (17) and (22) are constraints to establish that each collection point has only one successor. Equations (13), (18) and (23) are constraints to establish that each collection point has only one predecessor. Equations (14), (19) and (24) are constraints for the sub-tour elimination. Equations (15), (20) and (25) are binary constraints for the decision variables. Equations (16), (21) and (26) are non-negativity constraints for the decision variables. Appendix R shows the AMPL implementation of the described mathematical model.

7. Results

The results obtained detail the optimum route between the collection points for each island so that the cost is minimized for transportation, which is shown in Table 5 and the output for routes from the AMPL software can be found in Appendix S. Also, the optimum number of each type of truck available in each island for each day of the week can be seen from Table 6 to Table 8 and the output for trucks from the AMPL software can be found in Appendix T. At last, the optimum number of each type of container for each island can be found in Table 9 and the output for containers from the AMPL software can be found in Appendix U. The resulting cost from the optimization model is of $ 10.661 for the three islands, in comparison with the actual cost that the islands manage nowadays, which is of $ 18.662 for the whole transportation of solid waste per week.

Table 5. Routes between collection points for each island.

San Cristobal	1-17-20-22-3-5-10-2-18-11-16-15-14-13-12-4-19-21-23-9-8-6-7-1
Santa Cruz	1-8-7-3-9-2-5-6-4-1
Isabela	1-15-16-18-20-19-17-14-12-11-13-5-4-3-6-8-9-10-7-2-1

Table 6. Number of trucks needed for each day of the week in San Cristobal.

San Cristobal			
	Small	**Medium**	**Big**
Monday	-	-	1
Tuesday	1	-	1
Wednesday	-	-	1
Thursday	1	-	1
Friday	-	-	1
Saturday	-	-	1
Sunday	-	-	1

Table 7. Number of trucks needed for each day of the week in Santa Cruz.

Santa Cruz			
	Small	**Medium**	**Compactor**
Monday	-	-	4
Tuesday	2	-	1
Wednesday	-	-	4
Thursday	2	-	1
Friday	3	-	3
Saturday	2	-	1

Table 8. Number of trucks needed for each day of the week in Isabela.

Isabela			
	Small	**Medium**	**Big**
Monday	1	-	-
Tuesday	1	-	-
Wednesday	1	-	-
Thursday	-	1	-
Friday	1	-	-
Saturday	1	-	-

Sunday	1	-	-

Table 9. Number of containers needed per week in each island.

	San Cristobal	**Santa Cruz**	**Isabela**
Small	1	-	-
Big	1	4	1

8. Sensitivity analysis.

For the sensitivity analysis, a first scenario is considered with the current level of waste that is collected based on the population; a second scenario where the optimum number of trucks and containers for the actual situation of waste generation is considered. Then a third scenario where the generation of waste increases in parallel, as the population increases by 9.5%. This percentage based on the census carried out in 2015 by INEC, where a population increase of 9.5% was calculated, from 2010 to 2015. And finally, a fourth scenario where the population doubles, and therefore its generation of waste. Scenario that was chosen, because it represents the worst case that the waste management system could face. The sensitivity analysis for the four scenarios is shown from Table 10 to Table 12 for each island.

Table 10. Sensitivity analysis for San Cristobal.

Type of transportation	**Size**	**Actual quantity**	**Actual quantity with optimum proposal**	**Increment of 9,5% in population**	**Increment of 50% in population**
Containers	67 m^3	5	1	1	2

	33 m^3	2	1	1	-
	1,5 ton	7	2	2	2
	2 ton	7	-	-	-
Trucks	4 ton	7	7	7	9
	4 ton (compactor)	-	-	-	-

As a result, in table 10 it was found that the container with capacity of 67 m^3 increases it's quantity only for fourth scenario. In the other hand, the container with capacity of 33 m^3 is not used in fourth scenario since it is replaced by a bigger container. Meanwhile, the result for trucks show that the smaller truck doesn't change over time as population increases and the truck with capacity of 4 ton increases by two trucks for the fourth scenario.

Table 11. Sensitivity analysis for Santa Cruz.

Type of transportation	**Size**	**Actual quantity**	**Actual quantity with optimum proposal**	**Increment of 9,5% in population**	**Increment of 50% in population**
Containers	67 m^3	5	4	4	6
	33 m^3	4	-	1	-
Trucks	1,5 ton	24	9	2	3
	2 ton	-	-	1	-
	4 ton	-	-	-	-
	4 ton (compactor)	12	14	18	25

For table 11, the result found is that the container with capacity of 67 m^3 increases its quantity by two in the fourth scenario. In the other hand, the container with capacity of 33 m^3 shows an increment only for the third scenario given that for the fourth scenario the use of bigger containers is preferred. Meanwhile, the result for trucks show that the smaller truck used decreases for the last scenarios, this because the use of bigger trucks is preferred, reason why the truck with capacity of 4 ton increases by ten trucks for the fourth scenario.

Table 12. Sensitivity analysis for Isabela.

Type of transportation	**Size**	**Actual quantity**	**Actual quantity with optimum proposal**	**Increment of 9,5% in population**	**Increment of 50% in population**
Containers	67 m^3	3	1	1	1
	33 m^3	1	-	-	-
Trucks	1,5 ton	7	6	6	6
	2 ton	-	-	-	-
	4 ton	7	1	1	1
	4 ton (compactor)	-	-	-	-

It is considered that for the results of Table 12 a change isn't shown for the last three scenarios because the population in Isabela is small, so even a big increment isn't enough to pass the capacity of 13 kg in trucks and 67 m^3 in containers, but the waste generated is never less than 34 m^3 and 11 kg. Considering the costs established in Table 13 for using each type of container and truck, the cost in comparison with the capacity obtained for the different scenarios is shown from Table 14 to Table 16. The total cost and capacity for each scenario is shown in Table 17.

Table 13. Costs for using each type of container and truck.

Container		Truck	
67 m^3	$ 450	1,5 ton	$ 50
		2 ton	$ 70
33 m^3	$ 350	4 ton	$ 90
		4 ton (compactor)	$ 120

Table 14. Cost vs capacity for San Cristobal.

Type of transportation	**Size**	**Actual quantity**	**Actual quantity with optimum proposal**	**Increment of 9,5% in population**	**Increment of 50% in population**
Containers	67 m^3	$ 2.250 335 m^3	$ 450 67 m^3	$ 450 67 m^3	$ 900 134 m^3
	33 m^3	$ 700 66 m^3	$ 350 33 m^3	$ 350 33 m^3	-
Trucks	1,5 ton	$ 350 10,5 ton	$ 100 3 ton	$ 100 3 ton	$ 100 3 ton
	2 ton	$ 490 14 ton	-	-	-
	4 ton	$ 630 28 ton	$ 630 28 ton	$ 630 28 ton	$ 810 36 ton
	4 ton (compactor)	-	-	-	-

For table 14, the costs associated with the results described in Table 10 are calculated, finding that there is an increment in the optimum cost only for the fourth scenario where the population doubles.

Table 15. Cost vs capacity for Santa Cruz.

Type of transportation	Size	Actual quantity	Actual quantity with optimum proposal	Increment of 9,5% in population	Increment of 50% in population
Containers	67 m^3	$ 2.250 335 m^3	$ 1.800 268 m^3	$ 1.800 268 m^3	$ 2.700 402 m^3
	33 m^3	$ 1.400 132 m^3	-	$ 700 66 m^3	-
Trucks	1,5 ton	$ 1.200 36 ton	$ 450 13,5 ton	$ 100 3 ton	$ 150 4,5 ton
	2 ton	-	-	$ 140 4 ton	-
	4 ton	-	-	-	-
	4 ton (compactor)	$ 1.440 48 ton	$ 1.680 56 ton	$ 2.160 72 ton	$ 3.000 100 ton

For table 15, the costs associated with the results described in Table 11 are calculated, finding that there is a significant increment from scenario two to scenario three and form scenario three to the last scenario. Nevertheless, this cost is mostly associated with the increment in trucks for the third scenario and with both increment from containers and trucks for the fourth scenario.

Table 16. Cost vs capacity for Isabela.

Type of transportation	Size	Actual quantity	Actual quantity with optimum proposal	Increment of 9,5% in population	Increment of 50% in population
Containers	67 m^3	$ 1.350 201 m^3	$ 450 67 m^3	$ 450 67 m^3	$ 450 67 m^3
	33 m^3	$ 350 33 m^3	-	-	-
Trucks	1,5 ton	$ 350 10,5 ton	$ 300 9 ton	$ 300 9 ton	$ 300 9 ton
	2 ton	-	-	-	-
	4 ton	$ 630 28 ton	$ 90 4 ton	$ 90 4 ton	$ 90 4 ton
	4 ton (compactor)	-	-	-	-

For table 16, the costs associated with the results described in Table 12 are calculated, finding that there is a change only from the actual situation in comparison with the proposal for the same period of time, while the costs remain the same over the last scenarios.

Table 17. Summary of costs and capacities for each scenario for each island.

Island	Actual quantity	Actual quantity with optimum proposal	Increment of 9,5% in population	Increment of 50% in population

San Cristobal	Cost	$ 4.420	$ 1.530	$ 1.530	$ 1.810
	Capacity	401 m^3	100 m^3	100 m^3	134 m^3
		52,5 ton	31 ton	31 ton	39 ton
Santa Cruz	Cost	$ 6.290	$ 3.930	$ 4.900	$ 5.850
	Capacity	467 m^3	268 m^3	334 m^3	402 m^3
		84 ton	69,5 ton	79 ton	104,5 ton
Isabela	Cost	$ 2.330	$ 840	$ 840	$ 840
	Capacity	234 m^3	67 m^3	67 m^3	67 m^3
		38,5 ton	13 ton	13 ton	13 ton

9. Conclusions

A successful collection of information on the production and management of waste, collection points, costs, sales prices and management of recyclable waste was achieved for San Cristobal and Santa Cruz. However, writing mathematically the waste management of each island, was a problem due to the different waste management in each one of them.

Regarding the results obtained from this study through the proposed mathematical model, a value of $ 10,661 was obtained for waste management in the three islands, vs. a real value of $ 18,662. That is, a difference of $ 8001 a week, which a year would imply a saving of $ 416,052, for the three islands.

Finally, it should be mentioned that an optimization of the maritime route could not be carried out, since there is only one exit and delivery point for each island, and it is not possible to intervene on government decisions to build a new port. Although options for the optimization of maritime transport were taken into account, it was found that, regarding routes, ships already follow the best route according to geographical location.

Likewise, with respect to the approach of seeking the appropriate period of time in which container shipments should be made to the continent, it was concluded that it is not possible to intervene in this, since the ships are managed according to the demand for merchandise that they have to transport to the islands, but not the waste they must collect.

10. Future studies

10.1. Mathematical model that takes into account truck capacity and demand at different collection points.

Conclude the programming of an optimal route model that takes into account the capacity of the trucks and the demand at the different waste collection points. Being this the closest scenario to reality.

10.2. Mapping of all streets traveled.

Carry out a mapping of all the streets in which the truck collects waste, since at this moment in the model the established collection points represent a small limited portion of blocks. Within these blocks, around ten streets are visited for waste collection, and since the cost is per kilometer, the truck travels on average 10 times the actual distance established between points.

10.3. Find strategic collection points in Santa Cruz.

Find strategic collection points in Santa Cruz to change the matrix currently used in the model. This since the nine points used, only represent sectors around the island; plus, no delimited collection points, specifically selected for waste collection.

10.4. Ten-year projection of waste generation.

Carry out a 10-year projection of how much the amount of waste generated will increase, to assess the need for a new recycling plant on each island, to evaluate the possibility of generating new collection routes, with two starting points.

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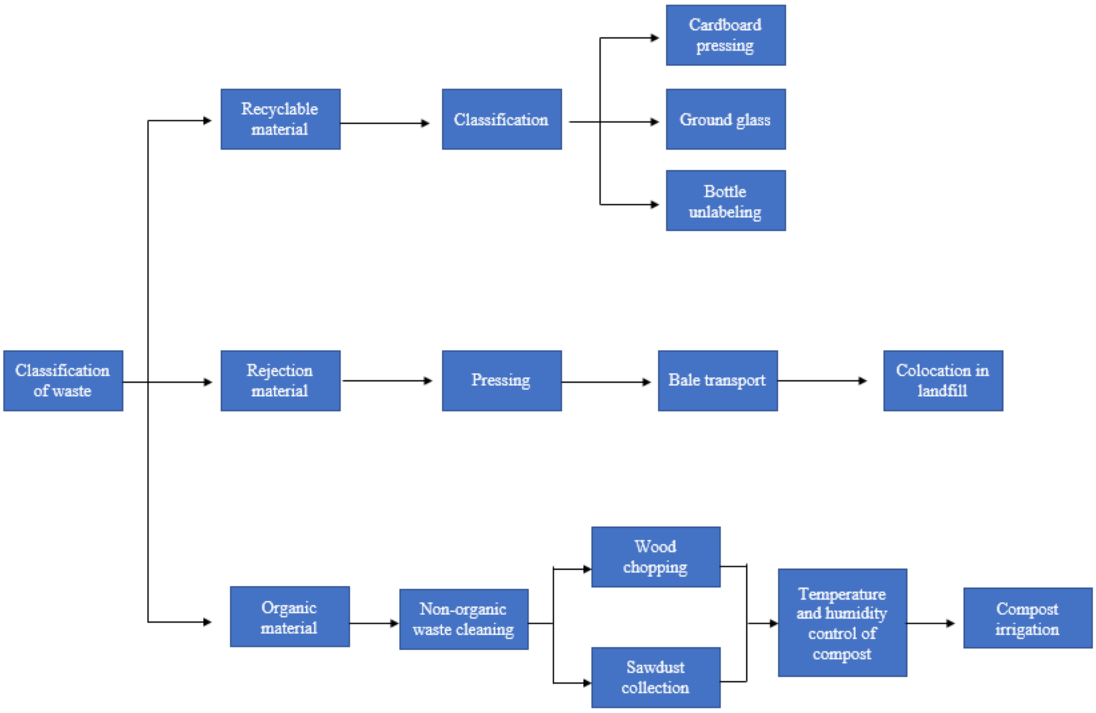
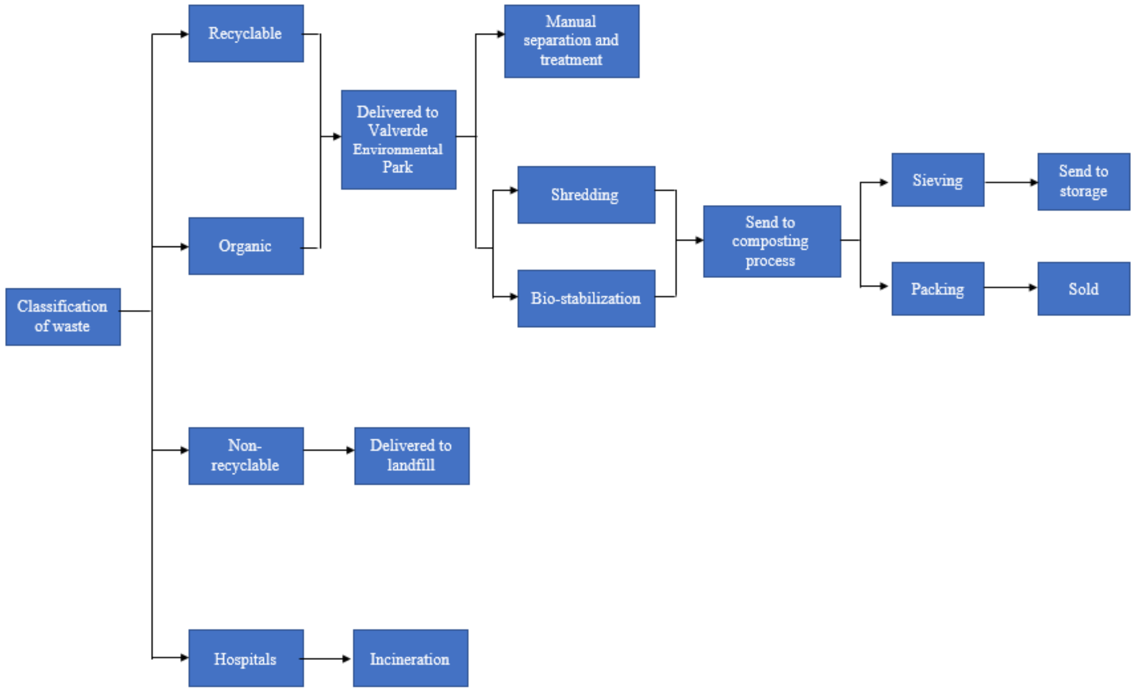
APPENDIX A: Waste management in San Cristobal (Alejandro & Terán, 2008).



APPENDIX B: Waste management in Santa Cruz (Ragazzi et al., 2014).



APPENDIX C: Types of waste generated monthly in 2019 in each island (GAD Santa Cruz, 2019 and GAD San Cristóbal, 2019).

Month	Santa Cruz			San Cristobal			Baltra
	Organic	**Rejection**	**Recyclable**	**Organic**	**Rejection**	**Recyclable**	**Recyclable**
January	124460	205840	150180	67395	110605	49248	14340
February	117710	190780	136860	49520	86823	33350	12520
March	120730	195290	140320	46860	74978	31530	13060
April	121300	193780	142960	38560	54320	29680	13340
May	122310	197240	141500	88635	86629	36220	13420

June	122800	196280	142070	45360	65800	29960	13490
July	118990	165480	131460	89835	90708	48134	9430
August	112379	171955	135244	95500	107819	44352	5970
September	117696	140228	133061	90715	104825	41855	8490
October	109703	155526	148146	76150	102052	42181	5540
November	127340	149140	142725	78055	94183	41950	9230
December	102714	157537	158880	74750	36840	55606	11758
Total	1418132	2119076	1703406	841335	1015582	484066	130588

APPENDIX D: Database with the collection of several news about specific dates of transportation of waste from Galapagos to Guayaquil.

Amount of waste sent to the continent	**Islands where it was collected**	**Date**	**Source**
22 ton	Floreana, Santiago, San Cristobal y Santa Cruz	apr-18	https://www.gobiernogalapagos.gob.ec/galapagos-sin-plasticos-de-un-solo-uso/

9000 ton	Santa Cruz, San Cristobal and Isabela	2018	https://www.elcomercio.com/tendencias/basura-rellenos-galapagos-islas-desperdicios.html
5000 ton	Santa Cruz	2015	https://www.elcomercio.com/tendencias/basura-rellenos-galapagos-islas-desperdicios.html
6100 ton	Santa Cruz	2018	https://www.elcomercio.com/tendencias/basura-rellenos-galapagos-islas-desperdicios.html
900 ton	Isabela	2018	https://www.elcomercio.com/tendencias/basura-rellenos-galapagos-islas-desperdicios.html
8 ton	Galápagos	1 Quarter 2019	https://www.elcomercio.com/tendencias/plastico-contaminacion-especies-galapagos-desechos.html
24,23 ton	Galápagos	2018	https://www.elcomercio.com/tendencias/plastico-contaminacion-especies-galapagos-desechos.html
6,47 ton	Galápagos	2017	https://www.elcomercio.com/tendencias/plastico-contaminacion-especies-galapagos-desechos.html
4,6 ton	Galápagos	1 Week feb-19	https://www.publicafm.ec/noticias/actualidad/1/galapagos-lucha-plastico
35000 tires	Galápagos	2012	https://www.publicafm.ec/noticias/actualidad/1/galapagos-lucha-plastico

100 ton	Santa Cruz y San Cristobal	Nov.-14	http://www.ambiente.gob.ec/82-toneladas-de-residuos-reciclables-evacuados-de-galapagos/
70 ton	San Cristobal	Aug.-15	http://www.ambiente.gob.ec/82-toneladas-de-residuos-reciclables-evacuados-de-galapagos/
12 ton	Isabela	Aug.-15	http://www.ambiente.gob.ec/82-toneladas-de-residuos-reciclables-evacuados-de-galapagos/
50 ton	San Cristobal	Aug.-15	http://www.ambiente.gob.ec/50-toneladas-de-residuos-reciclables-fueron-evacuados-de-las-islas-galapagos/
2 ton	San Cristobal	June-15	http://www.ambiente.gob.ec/mas-residuos-se-retiran-desde-galapagos-hacia-continente/
90 tires	San Cristobal	June-15	http://www.ambiente.gob.ec/mas-residuos-se-retiran-desde-galapagos-hacia-continente/
9,3 ton	San Cristobal	June-15	http://www.ambiente.gob.ec/mas-residuos-se-retiran-desde-galapagos-hacia-continente/
9 ton	San Cristobal	June-15	http://www.ambiente.gob.ec/mas-residuos-se-retiran-desde-galapagos-hacia-continente/
66 ton	Santa Cruz y San Cristobal	2015	http://www.ambiente.gob.ec/66-toneladas-de-residuos-inorganicos-aprovechables-fueron-retirados-de-las-islas-galapagos/
5300 tires	Santa Cruz y San Cristobal	2015	http://www.ambiente.gob.ec/66-toneladas-de-residuos-inorganicos-aprovechables-fueron-retirados-de-las-islas-galapagos/

4,6 ton	San Cristobal y Española	Feb.-19	http://www.galapagos.gob.ec/46-toneladas-de-basura-fueron-retiradas-de-las-costas-de-galapagos/

APPENDIX E: Waste generated per island in kg of the different types of recyclables (GAD Santa Cruz, 2019 and GAD San Cristóbal, 2019).

Island	**Month**	**Type of Recyclable**												
		Paperboar	**Scrap steel**	**Glass**	**PET**	**PEAT**	**Bulky**	**Plastics**	**Cans**	**Aluminum**	**Paper**	**Electronic**	**Tires**	**Tetra pack**
Santa Cruz	Jan.	35050	17780	28300	-	-	-	15940	2010	220	4350	45	189	1920
	Feb.	34793	15800	28990	-	-	-	15773	1989	310	4557	40	0	1793
	Mar.	33683	16420	28500	-	-	-	16110	1870	280	4630	50	20	1793
	Apr.	34000	13090	28650	-	-	-	15340	1250	240	4830	55	396	1810
	May	33340	13630	31000	-	-	-	16969	1130	0	4084	43	76	1900
	June	30570	12130	28650	-	-	-	14900	400	300	2464	47	90	1050
	July	30680	21030	27800	-	-	-	13886	320	0	5137	60	65	1667
	Aug.	30571	20213	22800	-	-	-	12296	990	0	1417	0	50	1515
	Sept.	27010	16088	29400	-	-	-	13492	550	950	5770	123	152	1551

	Oct.	33340	16403	32450	-	-	-	14369	1300	240	7320	53	55	1762
	Nov.	22551	17570	26300	-	-	-	8422	1580	400	4624	27	98	1205
	Dec.	30207	7713	36420	-	-	-	16042	5231	1523	6250	8	47	2520
	Total	375795	187867	349260	-	-	-	173539	18620	4463	55433	551	1238	20486

Island	Month	Type of Recyclable												
		Paperboa	Scrap	Glass	PET	PEAT	Bulky	Plastics	Cans	Aluminu	Paper	Electronic	Tires	Tetra
San Cristobal	Jan.	13090	3720	8960	2300	910	810	4020	260	180	370	800	-	-
	Feb.	5780	3080	5040	1680	270	900	2850	230	0	350	800	-	-
	Mar.	7860	2310	1680	1030	0	620	1650	0	450	0	0	-	-
	Apr.	6410	3700	2800	810	250	550	1610	230	0	0	0	-	-
	May	12200	3360	6790	920	850	640	2410	250	0	350	500	-	-
	June	12810	3870	8560	470	430	610	1510	500	0	70	400	-	-
	July	8580	6890	7241	1010	650	870	2530	460	0	450	550	-	-
	Aug.	8780	4000	5130	770	460	540	1770	440	230	0	1150	-	-
	Sep.	6230	4920	3250	480	800	1570	2850	460	180	460	510	-	-

Oct.	8635	3900	3900	740	440	1100	2280	260	150	360	600	-	-
Nov.	10080	3580	6400	820	430	430	1680	250	0	0	300	-	-
Dec.	9200	3630	4800	510	570	570	1650	290	0	0	800	-	-
Total	109655	46960	64551	11540	6060	9210	26810	3630	1190	2410	6410	-	-

APPENDIX F: Days in which each type of waste is collected in San Cristobal (GAD San Cristóbal, 2019).

Type of waste	**Collection days**						
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Organic	X		X		X		X
Recyclable		X		X			
Rejection		X		X		X	
Dangerous					X		
Paperboard from shopping area		X		X			

APPENDIX G: Collection route of solid household waste in San Cristobal (GAD San Cristóbal, 2019).

Route number	Neighborhood	Collection time		Minutes
		Beginning	End	
1	Market	6:00 a. m.	6:10 a. m.	10
2	Central	6:10 a. m.	6:30 a. m.	20
3	Armada	6:30 a. m.	6:55 a. m.	25
4	Frío	6:55 a. m.	7:20 a. m.	25
5	San Francisco	7:20 a. m.	7:45 a. m.	25
6	Airport	7:45 a. m.	7:50 a. m.	5
7	Estación Terrena	7:50 a. m.	8:35 a. m.	45
8	Barrio	8:35 a. m.	9:05 a. m.	30
9	Fragata	9:35 a. m.	10:05 a. m.	30
10	Albatros	10:05 a. m.	10:35 a. m.	30
11	Cactus	10:35 a. m.	11:00 a. m.	25
12	Peñas Altas	11:00 a. m.	11:40 a. m.	40
13	Peñas Bajas	11:40 a. m.	12:15 p. m.	35
14	Divino Niño	12:15 p. m.	12:25 p. m.	10
15	Playa Mann	12:25 p. m.	12:35 p. m.	10

16	Playa de Oro	12:35 p. m.	12:45 p. m.	10
17	Market	12:45 p. m.	12:50 p. m.	5
18	Police station	12:50 p. m.	12:55 p. m.	5
19	Isla Sur	12:55 p. m.	1:00 p. m.	5
20	Maestro	1:00 p. m.	1:05 p. m.	5
21	Manzanillo	1:05 p. m.	1:20 p. m.	15
22	Palmeras	1:20 p. m.	1:35 p. m.	15
23	El Progreso	1:35 p. m.	2:00 p. m.	25

APPENDIX H: Truck of 4 tons for San Cristobal.

APPENDIX I: Areas in San Cristobal for waste collection (GAD San Cristóbal, 2019).

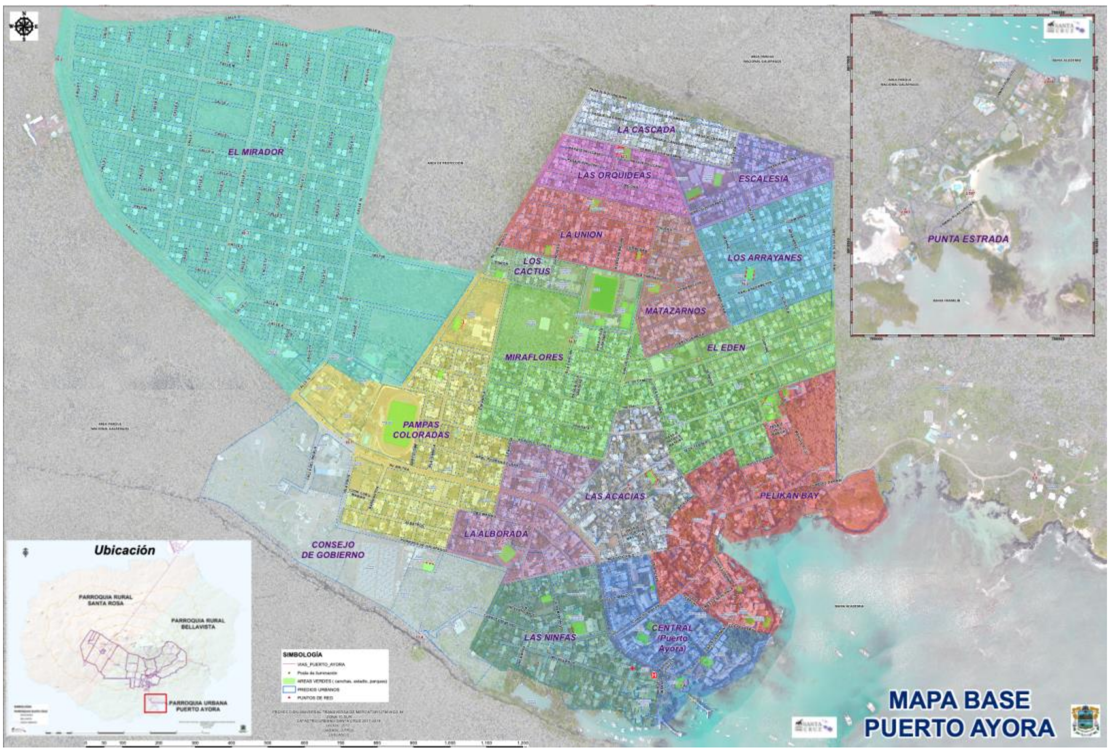
APPENDIX J: Itinerary of the times and days that each type of waste is collected in Santa Cruz (GAD, Santa Cruz, 2019).

Type of waste	Area	Time		Collection days						
		Begins	Ends	[illegible]	[illegible]	[illegible]	[illegible]	Friday	[illegible]	[illegible]
Organic	Commercial and residential area	7:00	12:00	X		X		X		
	Bellavista	9:00	12:00	X		X		X		

	Commercial and residential area	7:00	16:00	X		X		X	
Recyclable	Cascada	13:00	16:00	X		X		X	
	El Mirador	13:00	16:00	X		X		X	
	Rural area	7:30	13:00	X		X		X	
	Residential area	7:00	-		X		X		X
	Commercial area	16:00	-	X	X	X	X	X	X
Rejection	Santa Rosa	10:00	-	X		X		X	
	Bellavista	10:00	-	X		X		X	
	El Cascajo	10:00	-			X			X
Dangerous	Hospitals and laboratories	14:00	-		X			X	
Undergrowth	-	7:00	16:00		X		X		
Undergrowth	-	7:00	13:00						X
Scrap steel	-	7:00	9:00		X				X
Tires and cement bags	-	7:00	9:00		X		X		

APPENDIX K: Compactor truck.

APPENDIX L: Areas in Santa Cruz for waste collection (GAD Santa Cruz, 2019).



APPENDIX M: List of prices according to recyclable type at which the government sells the waste (O. Palma, personal communication, February 26, 2020).

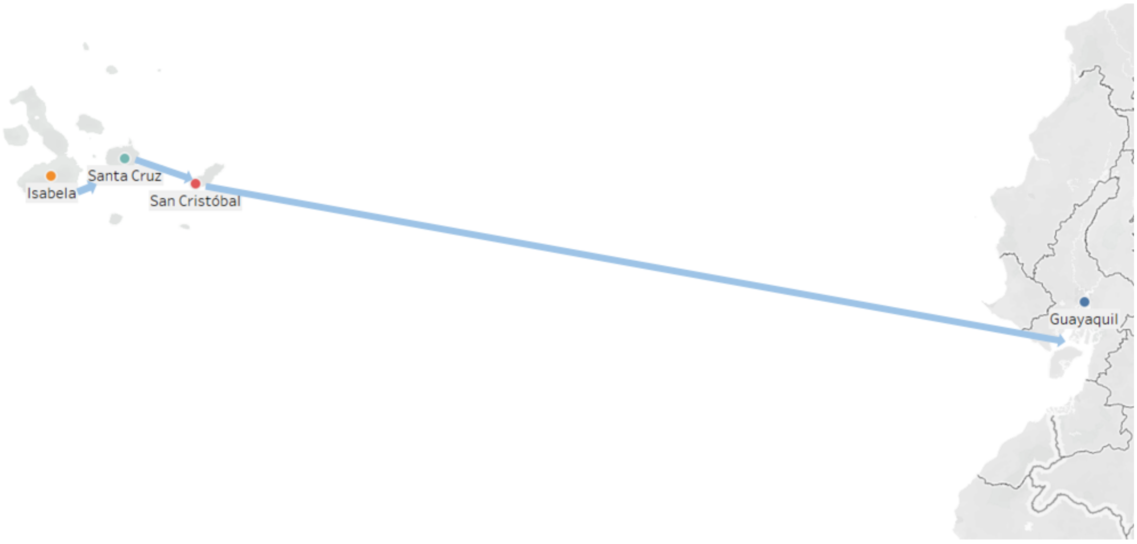
Type of waste	**Price per ton ($/ton)**
Paperboard	80
Scrap steel	100
Paper	20
Glass	20
Aluminum	200
PET plastic	350
PEAT plastic	60
Bulky plastic	60
Electronics	10

APPENDIX N: Weight of the bales according to type of recyclable (A. Zhunaula, personal communication, February 28, 2020).

Type of recyclable	**Weight (kg)**
Scrap steel	300 - 500

Plastic	90 - 150
Paperboard	150 - 250

APPENDIX O: Route followed by the vessel for waste collection (A. Zhunaula, personal communication, February 28, 2020).



APPENDIX P: Summary of the constraints found for each mathematical model can be found on the next link:

https://drive.google.com/file/d/1m1DYprUs0uTGcuYBB4PYj4019H98crri/view?usp=sharing

APPENDIX Q: Summary of the parameters found for each mathematical model can be found on the next link:

https://drive.google.com/file/d/1T0PqFLa13xmznPJvxTyVqJqAzRze_a0r/view?usp=sharing

APPENDIX R: AMPL implementation of the mathematical model.

```
set Contenedores;
set Camiones;
set day;
set typeWaste;
set typeWaste2;
set Islands;

param n_points;
set C:= 1..n_points;
param dista{n in C, k in C};

param n_points2;
set D:= 1..n_points2;
param dista2{t in D, l in D};

param n_points3;
set E:= 1..n_points3;
param dista3{r in E, v in E};

param daysperWaste{d in day, pp in typeWaste2, i in Islands};
param Can1 {o in Contenedores, i in Islands};
param Can2 {d in day, s in Camiones, i in Islands};
param Cost {s in Camiones};
param Cost2 {o in Contenedores};
param Cap1 {o in Contenedores};
param Cap2 {s in Camiones};
param pr{p in typeWaste};
param pe;
param vol;
param w{p in typeWaste, i in Islands};
param w2{pp in typeWaste2, i in Islands};
param f1;
param f2;
param f4;
param f5;
```

```
var x{o in Contenedores, i in Islands}, >=0, integer;
var z{d in day,s in Camiones, i in Islands}, >=0, integer;

var y{n in C, k in C} binary; # San Cristobal
var u{n in C} >= 0;

var y2{t in D, l in D} binary; # Santa Cruz
var u2{t in D} >= 0;

var y3{r in E, v in E} binary; # Isabela
var u3{r in E} >= 0;

minimize costo: f5*3 + sum {s in Camiones, i in Islands, d in day} Cost[s]*z[d,s,i] +
    sum{o in Contenedores, i in Islands} (x[o,i]*f1) +
    sum{o in Contenedores, i in Islands} (x[o,i]*f4) +
    sum{o in Contenedores, i in Islands} x[o,i]*Cost2[o] -
    sum{p in typeWaste, i in Islands} (pr[p]*w[p,i]);

minimize costo1: sum{n in C, k in C} dista[n,k]*y[n,k]*f2; # San Cristobal

minimize costo2: sum{t in D, l in D} dista2[t,l]*y2[t,l]*f2; # Santa Cruz

minimize costo3: sum{r in E, v in E} dista3[r,v]*y3[r,v]*f2; # Isabela
```

```
subject to r1 {i in Islands}:
    sum{o in Contenedores} (x[o,i]*Cap1[o]) >= sum{p in typeWaste} ((w[1,i])/pe)*vol;
subject to r2 {i in Islands, d in day}:
    sum{s in Camiones} (z[d,s,i]*Cap2[s]) >= sum{pp in typeWaste2} daysperWaste[d,pp,i]*(w2[pp,i]/7);
subject to r3 {i in Islands, o in Contenedores}: x[o,i] <= Can1[o,i];
subject to r4 {i in Islands, s in Camiones}: sum{d in day} z[d,s,i] <= sum{d in day} Can2[d,s,i];
subject to r12 {i in Islands}: sum{o in Contenedores} x[o,i] >= 1;
subject to r13 {d in day, i in Islands}: sum{s in Camiones} z[d,s,1] >= 1;
subject to r14 {d in day, i in Islands}: sum{s in Camiones} z[7,s,2] = 0;
subject to r15 {d in day, i in Islands}: sum{s in Camiones} z[d,s,3] >= 1;

# san cristobal

subject to
    r11 {k in C}: sum{n in C}y[n,k] = 1;
    r22 {n in C}: sum{k in C}y[n,k] = 1;
    r55 {n in C, k in C: n != 1 and k != 1 and n != k}:
        (u[n] - u[k] + card(C)*y[n,k]) <= card(C) - 1;

# Santa Cruz

subject to
    r111 {l in D}: sum{t in D}y2[t,l] = 1;
    r222 {t in D}: sum{l in D}y2[t,l] = 1;
    r555 {t in D, l in D: t != 1 and l != 1 and t != l}:
        (u2[t] - u2[l] + card(D)*y2[t,l]) <= card(D) - 1;

# Isabela

subject to
    r1111 {v in E}: sum{r in E}y3[r,v] = 1;
    r2222 {r in E}: sum{v in E}y3[r,v] = 1;
    r5555 {r in E, v in E: r != 1 and v != 1 and r != v}:
        (u3[r] - u3[v] + card(E)*y3[r,v]) <= card(E) - 1;
```

APPENDIX S: AMPL output for optimum routes in each island.

San Cristobal

y [*,*]

:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
3	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
12	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
18	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
22	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Santa Cruz

y2 [*,*]

:	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	1	0
2	0	0	0	0	0	0	0	0	1
3	0	0	0	1	0	0	0	0	0
4	1	0	0	0	0	0	0	0	0
5	0	0	0	0	0	1	0	0	0
6	0	1	0	0	0	0	0	0	0
7	0	0	0	0	1	0	0	0	0
8	0	0	0	0	0	0	1	0	0
9	0	0	1	0	0	0	0	0	0

Isabela

y3 [*,*]

:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
13	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

APPENDIX T: AMPL output for optimum number of trucks in each island each day.

San Cristobal

z [*,*,1]

:	1	2	3	4	:=
1	0	0	1	0	
2	0	1	1	0	
3	0	0	1	0	
4	0	1	1	0	
5	0	0	1	0	
6	0	0	1	0	
7	0	0	1	0	

Santa Cruz

```
 [*,*,2]
:   1   2   3   4     :=
1   0   0   0   4
2   0   2   0   1
3   0   0   0   4
4   0   2   0   1
5   0   3   0   3
6   0   2   0   1
7   0   0   0   0
```

Isabela

```
 [*,*,3]
:   1   2   3   4     :=
1   0   1   0   0
2   0   1   0   0
3   0   1   0   0
4   0   0   1   0
5   0   1   0   0
6   0   1   0   0
7   0   1   0   0
;
```

APPENDIX U: AMPL output for optimum number of containers in each island.

```
x :=
1 1   1
1 2   4
1 3   1
2 1   1
2 2   0
2 3   0
```