A reverse logistics network for recycling in Chile: a case in Concepción

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Abstract

Currently, pollution and poor recycling are global issues. Recycling is a widely used waste-management method throughout the world and contributes to eliminating waste efficiently and reduces the excessive use of natural resources. In this study, an optimized collection system of household recyclable material has been characterized and designed for cities with a low recycling level. To address this task, we propose a mathematical programming model that integrates two decisions, allocation and routing of different varieties of recycled products. First, the distance traveled by each customer and the costs associated with installing smaller collection centers are minimized. Subsequently, to minimize recyclable material transport, a route planning problem is solved by collecting from centers of greater capacity rather than from small centers, according to the traveling salesman problem. To illustrate our approach's usefulness, a numerical example based on the case of Chile's southern city is considered. The results suggest that the developed model is a practical tool for decision-makers in making tactical and operational decisions to reduce recycling costs.

Keywords: Recycling logistics, Supply Route optimization.

1. Introduction

Currently, pollution and poor recycling are global issues. Given the ease of communications and competition between companies, it has become essential to add value to proposed implementations to compete in the market. Despite the development and diffusion of new technologies occurring at accelerated rates, this is not reflected in the development of appropriate technologies or policies that manage all waste, especially electronic waste generated in developing countries. This issue causes problems in material handling and contamination as well as a greater environmental uncertainty regarding the “end” of many products (Tansel, 2017). Several authors consider recycling as part of the chain, that is, what takes place after the product is no longer used by the consumer, when it reaches the garbage and finally, a landfill, as a growing problem in current societies. Every day, more products are consumed and discarded at an accelerated rate (Johnsen et al., 2014). The global trend with respect to waste generation is shown in Table 1 and currently, the world is generating 2.01 billion tonnes of municipal solid waste annually. Worldwide, waste generated per person per day averages 0.74 kilograms varying from 0.11 to 4.54 kilograms. The amount of global waste is estimated to reach 3.40 billion tonnes by 2050 (Kaza et al., 2018).

Recycling is based on obtaining raw material or products from a waste and it can be total or partial, depending on each case. From some materials, it is possible to obtain the raw material to be used differently, whereas others require directly generating a new product. An example of an already used good is a plastic bottle. This bottle can go to the garbage or be recycled and thus acquire a new life cycle. Therefore, recycling contributes to eliminating waste efficiently and reduces the excessive use of natural resources. This process of the reuse of products and materials is known as reverse logistics (Agrawal et al., 2015; Govindan and Soleimani, 2017).

The most commonly recycled products are as follows: paper and cardboard, plastics in their multiple varieties and electric/electronic articles. Each of these wastes presents their own complexities of handling and treatment. Generally, recycling involves sorting operations that separate recoverable waste from the others and recycling plants where the wastes are finally recycled and/or stored (Edalatpour et al., 2018; Gold and Seuring, 2011; Heidari et al., 2019; Mohsenizadeh et al., 2020; Sheriff et al., 2017; Tansel, 2017). Plastic used in containers and packaging also has great potential to be recovered as a raw material for new products, reducing the cost of raw materials, limiting the use of natural resources, and decreasing the amount of waste generated. Therefore, the costs of landfill disposal are also reduced (Accorsi et al., 2014; Meherishi et al., 2019).

Table 1: Increasing trends in world population, plastic production and estimated quantities of electronic waste generated (Tansel, 2017).

Year	World population (billons)	World plastics production ton/years)	Obsolete computers in developing regions (million units)	Generation of domestic solid waste (million ton/day)	Electronic waste generated (million ton/year)
1960	3.03	15	0	1.5	n/a
1970	3.69	35	0	2.0	n/a
1980	4.44	69	0	2.5	n/a
1990	5.28	104	3	3.0	n/a
2000	6.10	185	50	3.2	n/a
2010	6.88	270	120	3.6	33.8
2015	7.21	300	200	4.0	43.8

One of the wastes that the fastest-growing is the waste of electrical and electronic equipment/e-waste that is estimated to reach 52 million tonnes in 2021. However, only around 20% of all e-waste generated is officially collected and recycled (Balde et al., 2017). For this reason, it has been widely studied; some reviews of them, see (Tansel, 2017; Islam and Huda, 2018; Doan et al., 2019). The last decade has been generated huge quantity works of empirical, theoretical or experimental research on logistics, waste management, and all levels of network design; for more details, we suggest reviewing Engeland et al. (2020). The authors do a complete revision of the integration of reverse supply chain and waste management literature.

In Latin America has been implemented pilot project by the organization including waste pickers that have provided good results (Ferri et al., 2015; Ferronato and Torretta, 2019; Franca et al., 2019; Olley et al., 2014). In fact, in the local context, Chile generated an average of 6.94 kg of electronic waste per inhabitant, reaching a total of approximately 112,984 tons, in 2014. Only 1.4% is recovered or managed for formal recycling. In addition, 62% of waste generation by large and small home appliances is concentrated in three regions: the Metropolitan Region (45%), the Biobío Region (12%) and the Valparaiso Region (10%) (Amphos 21 Consulting Chile, 2014). For plastics and other materials used for packaging, in 2010, a total of 1,223.264 tons was consumed. This value is equivalent to 71.5 kg per inhabitant (Eco-Ingeniería Ltda, 2012). Only since June 2016 has a regulation for solid waste been in place that consists of the "Framework Law for Waste Management, Extended Producer Responsibility, and Recycling Promotion" (Library of Congress of Chile, 2016). Under this Framework Law, manufacturers and importers of priority products must take care of their end-of-life products, such as lubricating oils, electronics, bulbs, newspapers and magazines, packaging, pharmaceutics, tires, batteries, expired pesticides and vehicles. Encouraged by this law, collection and recycling services in the private market has been begun to emerge. In fact, Banguera et al. (2018) proposed a reverse logistics network design under extended producer responsibility for the case of out-of-use tires in Santiago, Chile, in which the collection goals and penalties for the management system are established by a regulatory legal framework.

In the city of this study, Concepción, there are few means to carry out recycling of products. Some points receive waste of some kinds (mainly cardboards, papers, and plastics), but they are private initiatives to generate culture and improve the corporate image (Eco-Ingeniería Ltda, 2012). There are no municipal distribution and management channels for waste. The greatest obstacle to achieve an effective recycling system that covers a greater percentage of the generated waste is the lack of interested organizations (stakeholders) in the management of the waste. Besides, the problem is exacerbated by inefficient and unregulated management of waste and the nonexistence of formal collection entities (Bing et al., 2015). Considering these difficulties, to have an efficient operation, it is important to study the inter dynamics of decisions regarding collection centers' location, allocation, and routing of recycled products.

In this study, a decision model for integrating two decisions pertaining to the allocation and routing of different varieties of recycled products is proposed. To address this task, we propose a mixed-integer linear programming model (MILP) for capacitated facility location is developed in which recycling points are assigned to a set of customers and the routes of vehicles to centers of greater capacity. Thus, the proposed problem is a combination of two subproblems: the location balanced allocation problem and the traveling salesman problem, which are solved manner separately as well as integrally. The major contribution of our study is the development of a supply chain for recycling designed for cities with null or a low recycling level as the city of Concepción. By means, a decision model optimizes the supply chain for the recycling of certain products, reducing the recycling costs (installing recycling centers and transport of recyclable material) and thus increasing the city's environmental benefits.

The remainder of this paper is organized as follows: Section 2 describes the recycling problem and develops the model and the methodology adopted to solve the proposed model. The implementation of the model is illustrated using a case study, and its performance is evaluated in Section 3. Finally, we conclude the paper with some remarks and future works in Section 4.

2. Problem description

The problem discussed in this research proposes that waste collection for recycling starts at the customer, is sent to an initial collection point (ICP), and finally is transported to a centralized return center (CRC). When customers have a product whose useful life has come to an end, they collect their own recyclable waste and deposit it in a designed ICP. This process is graphically represented in Figure 1. The ICPs receive garbage from different customers, and subsequently, this garbage is removed by a collecting vehicle to be transferred to a CRC with greater capacity. This process is represented graphically in Figure 1.

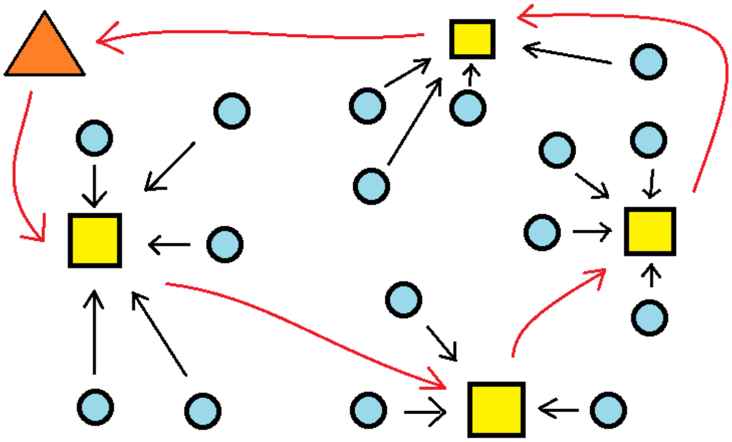

Figure 1. Problem representation.

There are initial nodes (circles) that represent customers, who are generators of recyclable material. Each node is separated from the others by a distance other than zero, and therefore, there are no customers located together in the same node. All customers are in a limited space where there are secondary nodes (squares), which are possible locations for ICPs for recyclable garbage deposition. Once the garbage has been deposited by customers, a collecting vehicle removes the content from the square recycling nodes and transports it to the ICPs (triangular node). Then, the obtained material can be treated to some kind of recycling process, according to the kind of waste.

Collection points have limited capacity and associated installation costs; additionally, they are in different locations of the area under analysis with a distance greater than zero between each of them. According to the above, we make the following assumptions:

- Each customer goes to the ICP to deposit their recyclable garbage.
- Each customer has only one assigned ICP.
- Transportation costs are directly proportional to the distance traveled (Sheriff et al., 2017).
- Each customer has a constant monthly production of garbage (determined according to existing data on this topic).

2.1. MILP model

The proposed problem consists of the recycling points must be assigned to a set of customers and to minimize the transport of recyclable material, the route planning problem is solved by collecting from centers of greater capacity rather than from small centers Thus, it is a combination of two subproblems: 1) the location balanced allocation problem; and 2) the traveling salesman problem, which are solved separately. In Table 2, we present the nomenclature of the mathematical model with the sets, indexes, parameters and decision variables. In the following subsections, the formulation of these two subproblems is described.

Table 2: The nomenclature of the MILP model.

Sets	Description
I	Set of customers.
J	Set of ICPs.
J_c	Set of ICPs that includes a CRC.
Indexes	
i	Index for Customer*s*.
j	Index for ICPs.
Decision variables	
x_{ij}	Binary variable. 1 if customer *i* is assigned to ICP j, 0, otherwise;
N_j	Binary variable. 1, if ICP j is open, 0, otherwise;
n_j	Integer variable. Number of customers assigned to ICP j.
V_j	Integer variable. Number of units allocated to ICP j.
y_{jk}	Binary variable. 1, if vehicle travels from ICP location j to ICP location j', 0, otherwise
u_j	Intermediate variable, non-negative and real number of ICP j.
Parameters	
q_i	Units of returned recyclable product from customer *i*.
Q_j	Capacity of ICP j.
FC_j	Fixed cost for establishing ICP j.
D_{ij}	Distance from customer *i* to ICP j.
$D_{jj'}$	Distance between ICPs j and j'.
D_{max}	Distance maximum between a customer and ICP.

2.1. 1 Phase I: Location balanced allocation problem

In phase I, we solve the problem of determining the location of the ICPs and allocating a customer to each ICP at the minimum cost, but in a balanced manner. This problem is referred to as the location balanced allocation problem (LBAP). The objective of this LBAP is to minimize the following costs as shown in (1):

i) Variable cost: the sum of the distances traveled by each customer to arrive at their assigned ICP.
ii) Fixed cost: the cost of establishing the ICPs, including land purchase/lease, building structure, and property tax.

$$\text{Minimize} \quad \sum_{i\in I}\sum_{j\in J} D_{ij}\, x_{ij} + \sum_{j=1}^{|J|} FC_j N_j \tag{1}$$

Subject to:

$$\sum_{j\in J} x_{ij} = 1, \qquad \forall\, i \in I \tag{2}$$

$$\sum_{i\in I} x_{ij} = n_j, \qquad \forall\, j \in J \tag{3}$$

$$\sum_{i\in I} q_i\, x_{ij} \le Q_j N_j, \qquad \forall\, j \in J \tag{4}$$

$$\sum_{i\in I} q_i\, x_{ij} = V_j, \qquad \forall\, j \in J \tag{5}$$

$$D_{ij}\, x_{ij} \le D_{max}, \qquad \forall i \in I, \forall j \in J \tag{6}$$

$$x_{ij} \in \{0,1\}, \qquad \forall i \in I, \forall j \in J \tag{7}$$

$$N_j \in \{0,1\}, \qquad \forall j \in J \tag{8}$$

$$V_j \in \mathbb{N}, \ \forall j \in J \tag{9}$$

$$n_j \in \mathbb{N}, \ \forall j \in J \tag{10}$$

Constraint (2) ensures that each customer is allocated to only one ICP. Constraint (3) determines the total number of customers allocated to an ICP. Constraint (4) ensures that the total volume of units allocated to each ICP never exceeds its capacity. Constraint (5) determines the total volume of units allocated to each ICP. Constraint (6) states that each customer can walk a maximum distance to arrive at an ICP. Finally, (7), (8), (9) and (10) define the domain of the variables.

2.1.2 Phase II: Traveling salesman problem

To collect all the recyclable material in its assigned ICP, the traveling salesman problem (TSP) is used. The objective of this TSP is the minimization of cost/distance to perform optimal tours from assigned ICPs to their CRC. This subproblem is formulated as follows:

$$\text{Minimize} \quad \sum_{j \in J_c} \sum_{k \in J_c} D_{jk}\, y_{jk} \tag{11}$$

Subject to:

$$\sum_{j \in J_c} y_{0k} = 1 \tag{12}$$

$$\sum_{j \in J_c} y_{j0} = 1 \tag{13}$$

$$\sum_{j \in J} y_{jk} = 1, \ \forall k \in J \tag{14}$$

$$\sum_{k \in J} y_{kj} = 1, \ \forall j \in J \tag{15}$$

$$u_j - u_k + (|J| - 1)\, y_{jk} \leq |J| - 2, \qquad \forall j \in J, \forall k \in J \tag{16}$$

$$y_{jk} \in \{0,1\}, \qquad \forall j \in J_c, \forall k \in J_c \tag{17}$$

$$u_j \geq 0, \qquad \forall j \in J \tag{18}$$

The objective of this TSP is to minimize the sum of distances traveled by each assigned ICP to arrive at their CRC as shown in (11). Constraints (12) and (13) ensure that the route starts and ends at the CRC. Constraint (14) ensures that each vehicle visits each ICP only once. Constraint (15) ensures that the vehicle leaves each ICP location once. Constraint (16) ensures avoidance of any subtours. Finally, (17) and (18) define the domain of the variables.

3. Results and Discussion

In this section, the proposed approach is tested with the case of Concepción, Chile. The performance of the proposed model has been tested by conducting a series of experiments on an Intel Core 7500U with 4-core 2.70 GHz and 16 GB of RAM, using the Debian GNU/Linux 9 (stretch) 64-bit operating system (by using single thread) and the software IBM ILOG CPLEX Studio IDE with Studio OPL 12.7.1.

To test the proposed models, different test instances are available. First, the data and compiled parameters are described according to the contextualization of the situation. Then, the test cases are detailed, and finally, a summary of results is shown. The center of the city of Concepción (Figure 2) is shown with 182 customer nodes (one block), 11 nodes corresponding to possible locations of initial recycling centers and one larger collection center that will collect the material accumulated in the initial centers. On the locations of the different points of initial recycling, possible locations to install larger centers with spaces for the free transit of people and vehicles were identified, without generating obstructions in the flow of traffic.

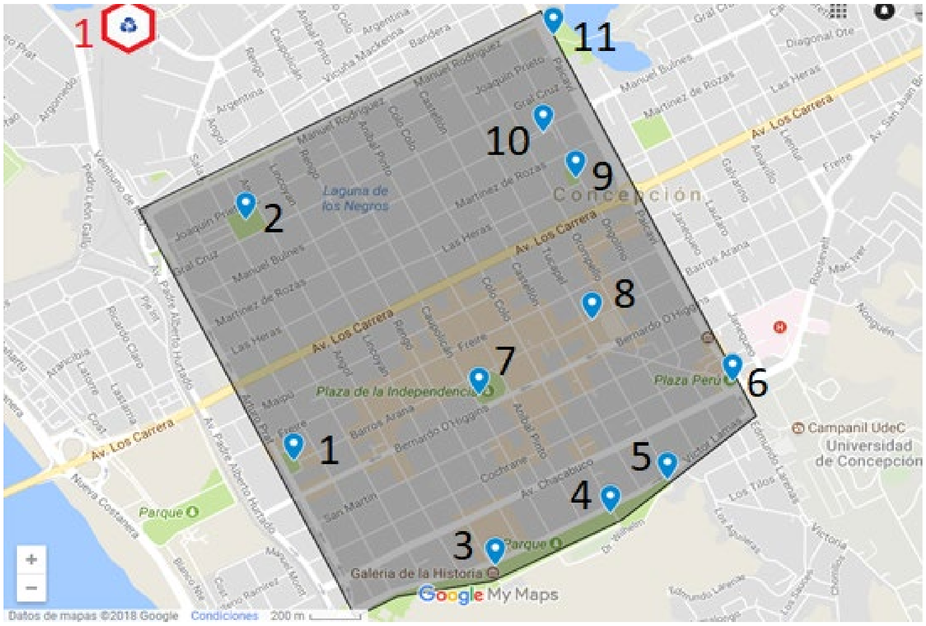

Figure 2: A block in the center of Concepción.

Costs and capacities of the initial collection centers are defined using data from a real case of recycling containers. In addition, it was assumed that the characteristics of the possible initial collection centers are equally defined for all cases in terms of capacity and cost, located in different points of the trial space of the case study (Yang et al., 2009). The amount of recyclable material was estimated according to national statistics (Amphos 21 Consulting Chile, 2014; Eco-Ingeniería Ltda, 2012) and considering the number of inhabitants in the analyzed area, using the population density in the urban area of Concepción. Data for the base instance are shown in Table 3. In Table 4, we present the results for the instances generated; for each instance, we provide the id ICP, the open or closed state of the ICP, the number of assigned customers and the amount processed in kg/month.

Table 3: Data to determine the material flow and capacity of the ICP.

Item	Value	Measuring unit
Average generation of garbage to be recycled	72.28	kg/year/person
Percentage of garbage currently recycled	1.4	%
Average recycling per person and year	1.01	kg/year/person
Average recycling per person and month	0.084	kg/month/person
Urban population density in Concepción	4,871	people/km2
Approximate amount of people per block	79	people
Recycling material per block (customer) in sampling area	7	kg/month
Cost of initial recycling point	5.000.000	dollars
Volume of Container of 20 feet	33,2	m3
Percentage of used volume	50	%
Density of household recyclable garbage	111,67	kg/m3
Capacity of an initial recycling point (container)	1854	kg

In the following, we present computational experiments to assess the proposal and to analyze the benefit of our approach in different test instances. In particular, in Instance 2, the amount of recyclable material transferred by each customer to the recycling center differs from that in Instance 1. For the recycling percentage, the European case of 2001 was considered, where 23% of recycled garbage was recorded European Environment Agency (2013). Accordingly, each customer node generates 7 kg/month of recyclable material at 110 kg/month. In Instance 3, the cost of the ICP was decreased by half.

Table 4: Results obtained for the proposed instances

Instance 1											
Id ICP	1	2	3	4	5	6	7	8	9	10	11
Open	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes	No
Assigned customers	33	37	0	0	25	0	44	0	0	43	0
Kg/month	231	259	0	0	175	0	308	0	0	301	0
Id ICP	1	2	3	4	5	6	7	8	9	10	11
Instance 2											
Id ICP	1	2	3	4	5	6	7	8	9	10	11
Open	Yes	Yes	No	Yes	No	No	Yes	Si	No	Yes	No
Assigned customers	33	33	0	20	0	0	33	30	0	33	0
Kg/month	1815	1815	0	1100	0	0	1815	1650	0	1815	0
Instance 3											
Id ICP	1	2	3	4	5	6	7	8	9	10	11
Open	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes	No
Assigned customers	33	37	0	0	25	0	44	0	0	43	0
Kg/month	231	259	0	0	175	0	308	0	0	301	0
Id ICP	1	2	3	4	5	6	7	8	9	10	11
Instance 4				Instance 5				Instance 6			
Id ICP	30	23		83	50	30		140	134	49	43
Open	Yes	Yes		Yes	Yes	Yes		Yes	Yes	Yes	Yes
Assigned customers	26	24		29	36	35		46	45	47	44
Kg/month	182	168		203	252	245		322	315	329	308

Instances 4, 5 and 6 assumed that the recycling centers can be located anywhere in the area under study, i.e., the customer nodes are also possible places to install an initial recyclable center. In those instances, there are 50, 100 and 182 nodes, respectively, of possible locations for initial centers. In Tables 5 and 6, the columns represent the instance, number of customer nodes, number of ICPs, number of binary variables, number of integer variables, number of constraints, number of iterations, computing time (second), optimal solution and objective (dollars). In Table 5, it observes that the three first instances, which correspond to the most realistic cases, obtained optimal solutions in short computing times. In the remaining instances, we can observe the tractability of the models as the size of the problem increases; the computing time increases, but the models are still tractable.

Table 5. Results obtained by CPLEX.

Instance	|I|	|J|	Binary variables	Integer variables	Constraints	Iterations	Computing time (sec.)	Optimal solution	Objective (dollars)
1	182	11	2013	22	2217	50	0.03	Yes	$ 35,824
2	182	11	2013	22	2217	25714	1.01	Yes	$ 42,959
3	182	11	2013	22	2217	50	0.03	Yes	$ 17,967
4	50	182	2550	100	2700	11027	1.17	Yes	$ 21,481
5	100	100	2013	200	10400	831984	237.39	Yes	$ 14,309
6	182	182	33306	364	33852	839267	93.36	Yes	$ 28,681

3.1 Impact of Decomposition

In order to evidence that the separated model is not suboptimal, we integrate the models and consider the sum of the objective function (1) and (11) as:

$$\text{Minimize} \quad \sum_{i\in I}\sum_{j\in J} D_{ij}\, x_{ij} + \sum_{j=1}^{|J|} FC_j N_j + \sum_{j\in J_c}\sum_{k\in J_c} D_{jk}\, y_{jk} \tag{19}$$

with the constraints (2)–(10), (12)–(18), and the following additional constraints are added:

$$\sum_{k\in J_c} y_{jk} = N_j, \qquad \forall\, j \in J_c \tag{20}$$

$$\sum_{k\in J_c} y_{jk} = \sum_{k\in J_c} y_{kj}\,, \qquad \forall\, j \in J_c \tag{21}$$

Constraint (20) ensures that only open ICPs are visited by the tour. Constraint (21) is the in-degree and out-degree constraint, i.e., the flow conservation constraint. With the two additional constraints, it is not necessary to consider constraints (14) and (15). Finally, the integrated model is composed using (19) as the objective function with constraints (2)–(10), (12), (13), (16)–(18), (20) and (21).

Table 6. Results obtained by CPLEX using the integrated model.

Instance	|I|	|J|	Binary variables	Integer variables	Constraints	Iterations	Computing time (sec.)	Optimal solution	Objective (dollars)
1	182	11	2157	22	2375	560	0.14	Yes	$ 35,824
2	182	11	2157	22	2375	4678	0.54	Yes	$ 42,957
3	182	11	2157	22	2375	489	0.12	Yes	$ 17,971
4	50	50	5151	100	5354	21696	2.95	Yes	$ 21,481
5	100	100	20301	200	20704	1052423	391.34	Yes	$ 14,309
6	182	182	66795	364	67526	1531939	1369.40	Yes	$ 28,681

Table 6 presents the results of the integrated model. We can observe that the integrated model obtains the same optimal solutions found by our proposed model. Therefore, our approach is not suboptimal, which is one major concern of decomposing the problem into two sequential subproblems. In addition, we can observe in Figure 3 that the integrated model has a substantial increase in computing times in the larger instances with respect to the integrated approach, such as in instance 4 that the separated model needs 237.39 secs and the integrated model requires 391.34. While in instance 5 there is much difference in the computing time to obtain the optimal solution and the separated model needs 93.36 secs the integrated model needs 1369.40 secs.

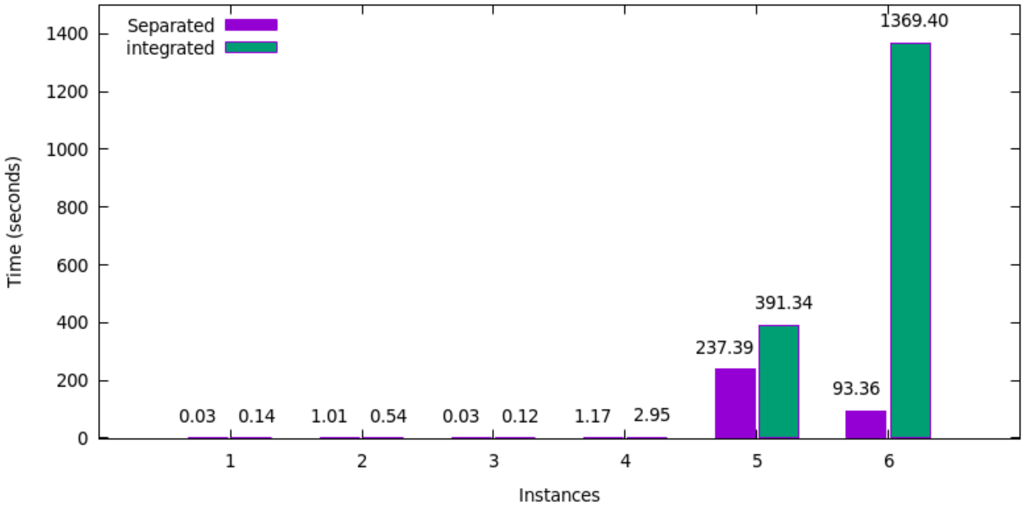

Figure 3: Comparison of computing times.

4. Conclusion

Although pollution has multiple causes, there are many opportunities for improvement in the field of recycling, both individually and collectively. In this study, research was carried out with an approach aimed at the supply chain of recyclable material collection for cities with a low recycling level. Thus, it was possible to characterize an optimized system for collecting household recyclable material, specifically in the city of Concepción, Chile.

The model allows visualizing the economic flow of the costs related to the inverse logistics process. This enables the management system to predict the costs of installing of initial recycling centers and the transport of recyclable material. Thus, the results suggest that the cost of installing an initial recycling center is a more important factor than the customer's distance from one of those centers. Therefore, extra restrictions should be considered concerning the distance traveled by each customer. Besides, because the problem is decomposed in two sequential subproblems, frequently this approach provokes suboptimal solutions, and for this very reason, we demonstrated that our approach is not suboptimal and even showed it has better performance in the larger instances.

Future works could cover the problem analyzed more precisely, such as a more detailed characterization of the recyclable material generated by the people, to prioritize space for larger recycling centers and proper conditions. Another possible research direction could focus on the fact that the population participates effectively, detects possible improvements, chooses the placement of recycling points, and researches other actions that motivate constant participation in recycling. This study is the starting point for future and more detailed analyses that can be applied to the community of Concepción and other cities with a low recycling level.

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