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Greedy randomized adaptive search procedure to design waste collection routes in La Palma

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ABSTRACT

This paper seeks to analyze application of a metaheuristic in the improvement in the design of routes for the collection of recyclable waste in the island of La Palma (Canary Islands, Spain). This work is a partial result of a technological and research transfer project aimed to analyze the route planning for collecting two portions of the recyclable waste, specifically paper and cardboard packaging and plastic packaging and cans, in this context. This scenario is modelled by an optimization problem termed Eco-efficient Vehicle Routing Problem. A mathematical model is proposed to formalize this problem. A Greedy Randomized Adaptive Search Procedure (GRASP) is applied to obtain approximate solutions in real-life scenarios. Its goal is to increase the amount of recyclable waste collected, prioritizing the collection of those containers with the highest fill level. Moreover, a fill level estimation of the containers based on an historical data analysis is also developed and integrated into the solution approach. The results obtained in the computational experiments reveal that the proposed solution approach is highly efficient and able to improve the current route planning according to eco-efficient metrics.

1. Introduction

The current waste management involves a large number of relevant challenges for modern society (Al-Salem, Lettieri, & Baeyens, 2009). Some of them are derived from the shortage of financial resources, the absence of multilateral agreements between local, regional, or national governments, the resistance from the population to live close to waste facilities, or the complexity to design and maintain waste collection strategies that satisfy the real demand, among others. These challenges are unavoidable associated with an unstoppable growth of waste generation worldwide. In fact, according to the data taken up in the report by Kaza, Yao, Perinaz, and Van Woerden (2018) for the World Bank Group, global waste generation is predicted to be kept growing during the next 30 years. The main reasons behind this fact are several factors such as urbanization, population increase, and standard of living, among others. All these issues have given rise to that the waste treatment is nowadays one of the most relevant challenges. This situation makes the management of solid waste a major environmental problem (Guerrero, Maas, & Hogland, 2013).

Cities, regions, and local governments are responsible to manage solid waste in their geographical areas. Consequently, they have the concern to implement an efficient and competitive process to manage solid waste. The need to provide a high quality service to the citizens and the importance of the environment and sustainable development make it necessary to devote large amounts of resources to the efficient management of urban solid waste. In fact, the management of solid waste is a critical affair for local governments around the world and sustainable development (Marshall & Farahbakhsh, 2013), especially in regions with reduced dimensions such as islands or areas with archipelagic conditions. Notwithstanding, local governments face problems that go beyond their resources and capabilities.

This work constitutes part of a technological and research transfer project. Its purpose is to evaluate and improve the management of recyclable waste at one of the major islands in the Canary Islands (Spain), specifically the island of La Palma. The public and private agents involved in the improvement of the waste recycling in La Palma have among their objectives to increase the recyclable waste collection efficiency. In this context, there are two main agents involved in the project. First, the national waste management company responsible for environmental care through recycling and the eco-design of packaging.

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This company seeks to ensure the sustainable medium- and long-term development of the recyclable waste management system, as well as its optimal operation so as to satisfy the current and future packaging waste and processing demands placed on those involved by society and government. The other relevant agent is the operator company, which is in charge of the logistics operations of recyclable waste collection. Both agents cooperate with each other to ensure an adequate management of recyclable waste.

The technological and research transfer project aims to evaluate and analyze the current strategies, aspects, principles, and resources involved in the collection and transport of two portions of recyclable waste around La Palma; the blue portion consisting of paper and cardboard packaging as well as the yellow portion that consists of plastic packaging and cans. This project is a pilot project carried out in a geographically limited area, such as La Palma, but with the premise that the developed solution approach can be eventually adapted to address features from other contexts and obtain high performance by taking into account new appropriated criteria and considerations. This project includes the study and treatment of data provided by the waste management company and the local authorities on the current recyclable waste collection process in the island of La Palma to propose improvements in its planning. The information related to the demand of recyclable waste collection, containers locations and their characteristics, routes details, time and cost of the routes performed by the operator company and the resulting volumes of recyclable waste in containers and vehicles, together with the constraints of the available resources allow to offer and assess potential alternatives in the planning of the recyclable waste collection routes. The national waste management company promotes this project with the strategic objective of increasing the amount of recycling waste in the long term and encouraging citizens to recycle. This is done by motivating them to transfer their non-recyclable waste to recyclable waste. In this regard, one of the main reasons that discourage the citizen to recycle waste is to find the recycling containers full or overflowing. This is one of the key elements that are taken into account in the proposed solution approach.

According to the previous discussion, this paper focuses on the collection of recyclable waste from the blue and yellow containers (the blue containers should contain paper and cardboard packaging and the yellow containers should contain plastic packaging and cans) and their delivery to the waste processing plants. More specifically, this work proposes a solution approach to improve the route planning from an eco-efficient perspective. We propose a waste collection model that aims to maximize the amount of paper and cardboard packaging and plastic packaging and cans collected in such a way that the environmental impact is minimized. For this purpose, the developed solution approach give collection priority to those containers whose fill level is estimated as high. This allows to reduce the probability of having full or overflowing containers, and the consequent dumping of waste outside the containers. Also, the reduction of fuel consumption that can be achieved through lower time per route, and accordingly designing greener and shorter routes, is compatible with our goal.

The scenario under analysis is addressed as an optimization problem termed Eco-efficient Vehicle Routing Problem (Ee-VRP). It involves the design of routes to be carried out by a fleet of vehicles considering an extended planning horizon of several working days. The problem can be considered as a multi-depot routing problem whose starting and ending route locations are known. Specifically, there are three starting and ending points for the routes, whose locations are in three municipalities of La Palma: Breña Alta, Mazo, and Los Llanos. In connection with this, the routes departs from starting depots and finishes in the ending waste processing plants. In a feasible solution of the Ee-VRP, each vehicle in the fleet must carry out a route for each day within the planning horizon. Each route is defined as a sequence of waste collection points to be visited by the vehicle. All the recyclable paper and cardboard packaging or plastic packaging and cans must be collected in each visit.

The main contributions of this paper can be described as follows:

1. Addressing the real optimization problem of recyclable waste collection and transport in the island of La Palma (Canary Islands, Spain) within the framework of technological and research transfer project.
2. Proposing a mathematical formulation to model the current collection problem in order to formalize the problem mathematically.
3. Proposing an approximate optimization technique based on the general framework of Greedy Randomized Adaptive Search Procedure to solve the Ee-VRP.
4. Assessing the solution approach proposed by comparing the current routing scheme to the results of the proposed optimization technique.

The remainder of this paper is organized as follows. Section 2 provides a literature review of the most highlighted works about waste management, especially those related to route planning. Section 3 describes the optimization problem. A mathematical formulation of the Ee-VRP is later presented in Section 4. Afterwards, Section 5 introduces the solution approach aimed at solving the Ee-VRP. Later, the computational experiments are presented and discussed in Section 6. Finally, the main conclusions and future works are included in the last Section 7.

2. Literature review

The papers found in the literature about waste management can be classified according to multiple criteria. On the one hand, one of the most extended is based on the type of waste to be treated. In this regard, the main types are residential waste (or garbage), industrial waste, recyclable waste, and health-care waste. The residential waste refers to an heterogeneous set composed of materials that are differentiated by their composition, which is derived from the community as well as its degree of industrialization and commercialism (Garvin, Cohen, & Dwyer, 2011). The industrial waste is that obtained as result of an industrial activity (Sahoo, Kim, Kim, Kraas, & Popov, 2005). Furthermore, recyclable waste contributes positively to protect the environment, minimizes the need for extracting, refining, and processing raw materials (Dat, Linh, Chou, & Vincent, 2012). Lastly, health-care waste poses a risk to human health when handled improperly (Alagöz & Kocasoy, 2008). In this paper, we focus our attention on the treatment of recyclable waste, mainly produced domestically and to a lesser extent by small retail businesses in the island.

On the other hand, location in which the waste collection is carried out is another relevant criterion when classifying papers found in the literature. In this regard, a wide range of problem variants can be identified. Firstly, the local governments in some cases establish a local waste facility shared by the community in which recycling is performed (Tung & Pinnoi, 2000). Secondly, kerbside collection (Sniezek & Bodin, 2006) is referred to the collection of household waste through containers with small dimensions near the houses. Despite this clear distinction on the basis of location, in this paper we address an intermediate scenario in which waste containers are dedicated to collect recyclable waste produced by residents in a neighbourhood, a few streets, etc. (Bodin, Mingozzi, Baldacci, & Ball, 2000).

Moreover, the environmental damage is joint to the gradual increase in the volume of waste generation. Taking into account the impact on the environment of the logistics operations associated with a given activity such as the waste management is gaining greater weight in recent years. In fact, this concern has given rise to the term *green logistics* (McKinnon, Browne, Whiteing, & Piecyk, 2015). This is a multilevel concept that encourages all stakeholders to assess and minimize the impact of logistics operations within a supply chain (Giusti, 2009). In this scenario, transportation is one of the harmful activities and with the highest environmental cost, expressed by means of CO_2 emissions and energy consumption. In particular, road transportation is one of the main contributors to fuel consumption and carbon dioxide equivalent emissions. Nowadays, the main stakeholders in the field of waste management are committed strongly to design more sustainable solutions. In this regard, green vehicle routing is considered as a branch of green logistics that takes into account explicitly externalities derived from the use of vehicles (*e.g.*, carbon dioxide-equivalents emissions) with the goal of minimizing them as much as possible through better planning (Bektaş, Demir, & Laporte, 2016).

In general terms, collecting waste by means of a fleet of trucks involves to design efficient routes that satisfy the service requirements in such a way that residents can dispose waste at a primary collection point without interruption (Nuortio, Kytöjoki, Niska, & Bräysy, 2006). Unfortunately, most of the initiatives aimed at collecting waste are nowadays focused on emptying containers on the basis of predefined schedules. However, it has been amply demonstrated that these approaches are highly inefficient. In particular, predefined schedules give rise to high fuel consumption, low use of existing assets, and collection of half-full containers, among others. For these reasons, a large number of municipalities and regional governments have clearly staked achieve convergence towards alternative proposals based on route optimization that considers tracking of waste levels and operational analytics. These proposals allow to reduce operative costs, recover investment costs, help to meet sustainability goals, and improve quality of service perceived by the residents.

The generation of routes is a well-studied optimization problem introduced by Dantzig and Ramser (1959) and termed Vehicle Routing Problem (VRP). Broadly speaking, this problem is aimed at designing routes for a fleet of vehicles in order to satisfy the demands of a set of customers while optimizing some criteria. In this study, the goal is to collect a set of waste containers. Also, it is worth mentioning that, in real-life scenarios, the routes are subject to length and temporary constraints, among others. It is known that the VRP and its many variants have been of the most broadly studied in the scientific literature over the last decades (Braekers, Ramaekers, & Van Nieuwenhuyse, 2016). The most conventional objective of the problem is to minimize the total cost traveled by the vehicles. However, this criterion can be guided in terms of reduction of negative externalities and eco-efficiency. This encourages to find suitable trade-offs between environmental cost and economic impact in routing problems.

According to the green perspective, the variants of the VRP can be classified as (i) the Green VRP (GVRP), (ii) the Pollution Routing Problem (PRP), and (iii) the VRP in Reverse Logistics (VRPRL). GVRP is aimed at minimizing the required energy, PRP tackles the minimization of greenhouse gas emissions, whereas VRPRL is related to the distribution aspects of reverse logistics (Lin, Choy, Ho, Chung, & Lam, 2014). In the following we review some relevant works about GVRP published over the last years. A mixed-integer linear formulation and a reduction procedure for the GVRP are presented by Leggieri and Haouari (2017). This formulation offers compactness and flexibility in comparison to previous proposals found in the literature. Furthermore, Poonthalir and Nadarajan (2018) propose a bi-objective fuel efficient Green Vehicle Routing Problem with varying speed constraint. A Particle Swarm Optimization is proposed to solve the problem. Tirkolaee, Hosseinabadi, Soltani, Sangaiah, and Wang (2018) propose a new model for the multi-trip Green Capacitated Arc Routing Problem in order to minimize the total cost, which includes the cost of generation and emission of greenhouse gases. In this case, the problem is solved by means of a hybrid genetic algorithm.

The waste management industry involves a large number of stakeholders. Some of these are citizens, authorities, companies aimed at collecting waste, agencies impacted by the collection activity, etc. Unfortunately, the goals of these collectives are usually conflicting. From the optimization perspective, the main objectives addressed in the literature are the environmental impact (Tavares, Zsigraiova, Semiao, & Carvalho, 2009), the number of vehicles (Hansmann & Zimmermann, 2009), the required staff (Hansmann & Zimmermann, 2009), the length of the collection routes (Ustundag & Cevikcan, 2008), the total time (Arribas, Blazquez, & Lamas, 2010), the balance of route lengths performed by different employees (López-Sánchez, Hernández-Díaz, Gortázar, & Hinojosa, 2018), or the service total cost (Arribas et al., 2010). The interested reader is referred to the works by Han and Ponce Cueto (2015) and Sulemana, Donkor, Forkuo, and Oduro-Kwarteng (2018) to obtain a comprehensive review of methods and optimization criteria. In this paper and according to the particular objectives of the waste management company, we focus our attention on firstly maximizing the fill level of the collected containers. In spite of this, we also assess the impact of the proposed routes in terms of fuel consumption, distance, and time, among others.

Finally, it is worth mentioning that, over the last years, some innovative and promising initiatives to optimize the waste collection based on Internet of Things systems and devices have appeared on the market (Navghane, Killedar, & Rohokale, 2016). An example is to use sensors that allow to monitor indicators such as fill level, tilt, and temperature of the containers (Ramos, de Morais, & Barbosa-Póvoa, 2018). In spite of the fact that these initiatives are gaining popularity because of their effectiveness, they are still highly expensive, and therefore not open to most of the scenarios. The objective of sensor-based systems is to obtain and report confident data about the whole waste collection process (Faccio, Persona, & Zanin, 2011). However, in the absence of such systems, it is necessary to exploit knowledge extracted from historical data in order to estimate the status of the process, and therefore to anticipate best strategies. Some highlighted examples can be found in the works by Lu, Chen, Peng, and Shen (2015) and Lu, Chen, Ho, and Wang (2016). In this regard, we use historical data about the collection process with the aim of estimating the fill level of the containers, and therefore designing routes to collect containers selectively.

3. Problem description

This section is aimed at describing the Eco-efficient Vehicle Routing Problem, in short Ee-VRP. This optimization problem consists of designing routes to be followed by a fleet of vehicles for each day within a planning horizon H of several days. Each vehicle of the fleet is required to follow a route in each day of the planning horizon. In this regard, a feasible route is a sequence composed of waste collection points to be visited by a collection vehicle. The objective function of the Ee-VRP aims to maximize the recyclable waste collected from containers during the planning horizon.

The Ee-VRP can be formally described by means of a complete directed graph, $\mathcal{G} = (\Theta, A)$. The definition of $\mathcal{G}$ includes $\Theta = \{\theta_1, \theta_2, \ldots, \theta_n\}$, which is a set of n locations and $A = \{(\theta_i, \theta_j): \theta_i, \theta_j \in \Theta, i \neq j\}$. Also, $P \subset \Theta$ represents the set of m waste collection points and is defined as $P = \{P_1, P_2, \ldots, P_m\}$. Furthermore, the set E is defined as $E = \{e_1, e_2, \ldots, e_r\}$, where each element $e_i \in E$ is the start or end location of the routes. Hence, $\Theta = E \cup P$, whereas $E \cap P = \varnothing$. A distance $d_{ij} \geqslant 0$ and a travel time are known for each arc $(\theta_i, \theta_j) \in A$.

A waste collection point, $P_i = \{c_1^i, c_2^i, \ldots, c_{l(i)}^i\}$, is composed of $l(i)$ containers, where c_j^i is the j-th container that belongs to the i-th waste collection point. This way, the set of all the containers is defined as follows:

$$C = \bigcup_{i=1}^{m} P_i \tag{1}$$

The containers in a waste collection point are dedicated to collect waste of similar type: paper and cardboard packaging (blue containers) or plastic packaging and cans (yellow containers). This means that containers of different types do not belong to the same waste collection point.

The set of waste collection points are collected by means of a fleet of vehicles denoted as $\mathcal{V} = \{v_1, v_2, \ldots, v_k\}$. Each vehicle can collect only one type of container: paper and cardboard or plastic packaging and cans.

Therefore, $P(v)$ is defined as the set of waste collection points that can be collected by vehicle $v \in \mathcal{V}$. It is worth mentioning that all the containers included into $P(v)$, $\forall\, v \in \mathcal{V}$ are dedicated to collect recyclable waste of similar type. We consider a horizon H consisting of several days; $\mathcal{H} = \{h_i, \ldots, h_f\}$ The origin location of vehicle $v \in \mathcal{V}$ is denoted as $o(v) \in E$, whereas $t(v) \in E$ denotes its target location. In addition, when a waste collection point is visited in a route, all its containers are collected. The vehicles in the Ee-VRP have unlimited capacity, in such a way that they can collect waste from the collection points with no limit. In practice, this means that the volume and weight of the collected waste is significantly lower than the capacity of the vehicles. However, the maximum duration of the route of the vehicle $v \in \mathcal{V}$ in day $h \in H$ is defined as W_{vh}, expressed in hours and derived from the working day of the truck drivers who perform the collection of recyclable waste.

Each container $c \in C$ has associated several parameters and information about its status. More specifically, every container $c \in C$ has a fill level $f(c, d)$, which indicates the normalized percentage of container capacity filled by waste and where d is the number of days since the last collection and a fill rate $q(c) \geqslant 0$ that determines the increase in the normalized percentage of container capacity by day. It is therefore assumed that each container $c \in C$ is filled over days according to $q(c)$. That is:

$$f(c, d) = \max(1, q(c)\cdot d + b(c)), \tag{2}$$

where $b(c)$ is the level of the container after collected. It should be noted that the larger the time period from the last collection, the higher the fill level. Also, the containers can be full, and thus no additional waste is allowed. $q(c)\cdot d + b(c) > 1$ indicates the container $i \in C$ is overflowing after d days since its last collection. Furthermore, each container $c \in C$ requires a collection time $s(c) \geqslant 0$. In practice, this time is mainly derived from the location of the container in the waste collection point and the driver skills. Accordingly, the time required to collect the waste included into the containers belonging to the waste collection point $i \in P$ is defined as follows:

$$s_i = \sum_{j=1}^{l(i)} s(c_j^i), \tag{3}$$

where $s(c_j^i)$ corresponds to the collection time of container c_j^i, and $s_i = 0$, $\forall\, i \in E$. Similarly,

$$f_i(d) = \frac{1}{l(i)} \sum_{j=1}^{l(i)} f(c_j^i, d), \tag{4}$$

corresponds to the fill level of the waste collection point i where $f(c_j^i, d)$ is the fill level of container c_j^i. In addition, it is assumed that each waste collection point $i \in P$ has been collected $d_i \geqslant 1$ days before the beginning of the planning horizon. For example, if a given waste collection point $i \in P$ has been collected the last Friday of a week and it is required to define the routes to be follow during the next week, $d_i = 3$, corresponding to the elapse of time between Friday and Monday.

In summary, the Ee-VRP consists of designing feasible routes for each day of the planning horizon and type of recyclable waste that will be carried out by the fleet $\mathcal{V}$ of vehicles that collect recyclable waste while maximizing the fill level of collected containers. In spite of the presence of this primary objective, the waste management company is also interested in, when possible, reducing the current number of routes, the fuel consumption, and the number of overflowing containers.

4. Mathematical formulation

Once the Ee-VRP has been described in Section 3, in the current section the sets of variables and restrictions that determine a feasible solutions of the problem are formally defined. Therefore, the Ee-VRP can be formulated by means of a Mixed-Integer Programming (MIP) as follows. First of all, we herein define the variables used in the model:

- X_{ijh}^v, binary variable set to 1 if vehicle v goes from location i to j in day h, $X_{ijh}^v = 0$ otherwise, $\forall\, i \neq j \in \Theta, v \in \mathcal{V}, h \in \mathcal{H}$.
- Y_{ih}^v, binary variable set to 1 if location i is visited by vehicle v in day h, $Y_{ih}^v = 0$ otherwise, $\forall\, i \in \Theta, v \in \mathcal{V}, h \in \mathcal{H}$.
- T_{ih}, real variable that represents the start time of the collection of waste at collection point i, $\forall\, i \in P$, during day h, $h \in \mathcal{H}$.

The constraints that state values of these variables that correspond to feasible solutions are the following.

$$\sum_{j \in P} X_{o(v)jh}^v = \sum_{j \in P} X_{jt(v)h}^v = 1 v \in \mathcal{V},\;\; h \in \mathcal{H} \tag{5}$$

$$\sum_{j \in \Theta} X_{jih}^v = \sum_{j \in \Theta} X_{ijh}^v i \in P,\;\; v \in \mathcal{V},\;\; h \in \mathcal{H} \tag{6}$$

$$\sum_{j \in \Theta} X_{ijh}^v \leqslant Y_{ih}^v i \in P,\;\; v \in \mathcal{V},\;\; h \in \mathcal{H} \tag{7}$$

$$T_{jh} \geqslant T_{ih} + s_i + t_{ij} - M\cdot\left(1 - \sum_{v \in \mathcal{V}} X_{ijh}^v\right) i, j \in \Theta,\;\; h \in \mathcal{H} \tag{8}$$

$$T_{ih} + s_i + t_{it(v)} \leqslant W_{vh} i \in \Theta, v \in \mathcal{V},\;\; h \in \mathcal{H} \tag{9}$$

$$um_{v \in \mathcal{V}} Y_{ih}^v \leqslant 1 i \in P, h \in \mathcal{H} \tag{10}$$

$$X_{ijh}^v \in \{0, 1\} i, j \in \Theta, v \in \mathcal{V},\;\; h \in \mathcal{H} \tag{11}$$

$$Y_{ih}^v \in \{0, 1\} i \in P, v \in \mathcal{V},\;\; h \in \mathcal{H} \tag{12}$$

$$T_{ih} \geqslant 0 i \in \Theta, h \in \mathcal{H} \tag{13}$$

Firstly, constraints (5) specify the start and end of each route at point o and f respectively, whereas the flow balancing at waste collection point is guaranteed by constraints (6). Constraints (7) determine that a waste collection point can be visited by a route only if this waste collection point has been assigned to that route. Constraints (8) ensure the connectivity of the routes while constraints (9) guarantee that the maximum working time is respected by all routes. Each waste collection point can be assigned to at most one route, as stated by constraints (10). Finally, constraints (11)–(13) define the variables domains.

Moreover, the set of days in the planning horizon in which the collection point $i \in P$ has been collected before day $h \in \mathcal{H}$ can be computed as follows:

$$\mathcal{D}_{ih} = \left\{ d < \frac{h}{\sum_{v \in \mathcal{V}} Y_{id}^v} \right\} \tag{14}$$

The number of days since the last collection of the point $i \in P$ in day $h \in \mathcal{H}$ is defined as follows:

$$\eta_{ih} = \begin{cases} h - \max(k\colon k \in \mathcal{D}_{ih}), & \mathcal{D}_{ih} \neq \emptyset \\ \mathcal{H}_i + h, & \mathcal{D}_{ih} = \emptyset \end{cases} \tag{15}$$

On the basis of the previous discussion the objective function of the Ee-VRP can be formally defined as follows:

$$\min \sum_{v \in \mathcal{V}} \sum_{i \in P} \sum_{h \in \mathcal{H}} f_i(\eta_{ih})\cdot Y_{ih}^v \tag{16}$$

where $f_i(\eta_{ih})$ is the fill level of the waste collection point $i \in P$ at day h after η_{ih} days since its last collection given by Eq. (4).

5. Solution approach

In this section, an approximate optimization technique aimed at solving the Ee-VRP is presented. Its design is encouraged by two main issues. Firstly, as discussed in the computational experiments, La Palma has several hundreds of collection points and the mathematical formulation proposed in Section 4 has a limited applicability in scenarios with such dimensionality as this. Secondly, in the middle term, the

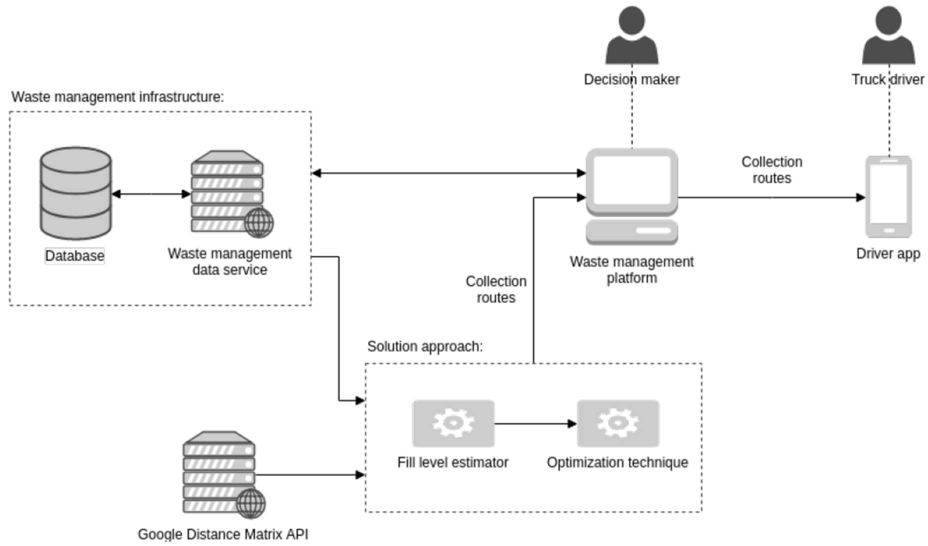


Fig. 1. General scheme of the solution approach integrated into the current technological infrastructure.

waste management company is highly interested in considering dynamic information of the environment, state of the traffic, main incidents, etc. when designing the collection routes. This means that the proposed technique should be inherently flexible to handle such information. For these reasons, it is required to count on versatile techniques able to report high quality solutions in short computational times.

In general terms, determining the set of collection points to be visited in each day of the planning horizon by each vehicle is the main decision to take in the optimization problem. However, it should be noted that the collection of containers in a day has a high impact on subsequent days of the planning horizon. This is derived from the fact that the containers are completely emptied when collected, and therefore the fill level of the involved containers is reduced to zero. At the same time, the larger the time period from the last collection, the higher the amount of recyclable waste, but increasing the risk of obtaining full or overflowing containers. This means that the decisions taken in a certain day give rise to changes in the quality of the collection routes in subsequent days. An intuitive framework based upon designing individual collection routes for each day of the planning horizon is hereafter discussed.

The proposed solution approach is integrated into the daily activity of the operator company as depicted in Fig. 1. The operator company owns a private waste management platform to monitor the collection and transport of recyclable waste to the existing waste processing plants. This platform is also used by the decision makers of the company to design the daily collection routes by hand. Nowadays, the routes are usually designed for weeks on end. Then, the routes are obtained by the truck drivers through a mobile application. The data gathered in the collection of containers is stored in a database system provided by the waste management company. These data can be consumed by means of web service endpoints, which enable to be integrated into other tools. In particular, our solution approach is embedded into the existing technological infrastructure as a black box. As can be seen in the figure, it exploits data stored by the waste management company and provides the collection routes to be followed by the truck drivers. Also, we use information provided through the Google Distance Matrix API[2] in order to obtain more accurate estimations about the travel times and distances in the routes. The proposed collection routes are checked by the decision maker of the operator company before sending to the truck drivers. It is worth mentioning that, in spite of the fact that, the decision maker is still present in the scheme, its role as route designer has been replaced and reduced to tackle unexpected events.

The proposed solution approach seeks to design the set of routes to be followed by the fleet of vehicles for each day within the planning horizon. It is based on the general framework of the Greedy Randomized Adaptive Search Procedure (Feo & Resende, 1995), hereafter GRASP. GRASP is a consistent multi-start two-phase meta-heuristic that has been applied for solving a wide range of real and large variants of routing problems. The scientific literature contains a large amount of combinatorial optimization problems solved by GRASP. The interested reader is referred to the work by Resende and Ribeiro (2010).

The pseudo-code of the solution approach is depicted in Algorithm 1. Firstly, it is required to know the distances and travel times between all the waste collection points (lines 1–2). The procedure is described in Section 5.2. The solution approach repeatedly gets good solutions by building a collection of routes (lines 4–18), and keeps the best in s_{best}, while the stopping criterion is not satisfied. It should be noted that at each step the solution under construction, s, is initially empty (line 5). This means that no feedback between consecutive iterations of the algorithm is considered. Then the solution approach builds a collection of routes (lines 8–12). These routes are designed in each day of the planning horizon, $h \in \mathcal{H}$ (line 6), for every vehicle, $v \in \mathcal{V}$ (line 7). This way, kH routes are built by the solution approach to obtain a feasible solution, s. In order to build a route, the set of waste collection points that can be collected by the vehicle v must be determined, $P(v)$ (line 8). This is the subset of all the points composed of containers aimed at collecting recyclable waste of the type collected by the vehicle v. In practice, v is not able to collect the recyclable waste associated with all the containers in $P(v)$ without breaking constraints derived from the maximum time of the routes. For this reason, it is firstly required to know the number of days since the last collection of the containers (line 9), and then a selection of waste collection points must be carried out. With this goal in mind, the fill level of all the containers included into $P(v)$ is determined (line 10). This process is described in Section 5.1. Furthermore, the individual routes are built by means of the method described in Section 5.3. Once a feasible route, r, is obtained, it is added to the solution under construction, s. In this regard, s will be feasible when a route for each vehicle and each day is defined.

[2] https://developers.google.com/maps/documentation/distance-matrix/start.

Algorithm 1. Pseudo-code of the proposed Greedy Randomized Adaptive Search Procedure aimed at solving the Ee-VRP

```
   Output: s_best. Best solution found during the search
1  d_ij ← Compute distances between P
2  t_ij ← Compute travel times between P
3  s_best ← ∅
4  while stopping criterion not satisfied do
5  |   s ← ∅
6  |   for h ∈ H do
7  |   |   for v ∈ V do
8  |   |   |   P(v) ← Waste collection points that can be collected by v
9  |   |   |   h(c), ∀c ∈ C ← Days since the last collection of container c
10 |   |   |   f(c, h(c)), ∀c ∈ C ← Determine fill level of containers
11 |   |   |   r ← Build route for v during day h
12 |   |   |   Add r to s
13 |   |   end
14 |   end
15 |   if s is better than s_best then
16 |   |   s_best ← s
17 |   end
18 end
19 return s_best
```

The construction method used to build individual solutions (Section 5.3) is non-deterministic. This means that, even using the same input data, different routes can be potentially reported in each execution. In this scenario, a multi-start procedure that repeatedly applies the construction method and outputs the best solution found over all trials is considered (lines 4–18). In each iteration, the last built solution, s, is compared with the best solution found by the algorithm, s_{best}. If s has a higher objective function value than s_{best} (Eq. (16)), or it has similar objective function but shorter total travelled distances or lower number of overflowing containers, the best solution is replaced by s. The multi-start procedure iterates until a given stopping criterion is met.

5.1. Estimated fill level

One of the most relevant elements when designing the collection routes of the waste management company is to establish the subset of containers to be collected by the fleet of vehicles in each day. In this regard, the company is interested in collecting only those containers with the highest fill level, in such a way that the optimization criterion can be maximized, but while avoiding the existence of overflowing containers. With the goal of determining the attractiveness of the containers to be collected, their fill levels are used. Unfortunately, due to the lack of sensorization associated with the containers in the environment under analysis, their fill levels must be estimated on the basis of the historical data stored by the waste management company or from other sources.

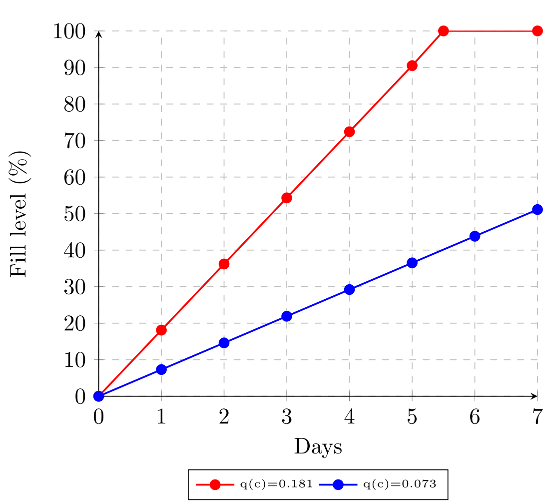


Fig. 2. Examples of fill rate.

The estimated fill level of a container $c \in C$ after h days since the last collection is computed by means of Eq. (2). However, in order to compute the estimated fill level, a fill rate, $q(c)$, is required to be known. In this case, according to the data stored by the company, it is reasonable to assume that the containers are filled lineally over time, but with heterogeneous fill rates. Fig. 2 depicts two examples of container with different fill rates. More advanced models that take into account social or geographic aspects, seasonal concerns, etc. are an open line for further research. As can be seen, the container is full after 5 days when the fill rate is 0.181 (red line), whereas this time is longer when fill rate is 0.073 (blue line). In this regard and as indicated in Section 3, a container c is estimated to be overflowing when $q(c)\cdot h + b(c) > 1$ after h days. This is useful for decision makers because this function allows to estimate the amount of recyclable waste not collected as well as the time during the container has been full before its collection.

5.2. Estimated distances and travel times

In spite of the fact that maximizing the fill level of the collected containers is the optimization criterion in the problem, the decision makers are also interested in obtaining routes with reasonable distance. In addition, the routes are constrained by the working day of the drivers. For these reasons, the distance and travel times between each pair of collection points should be known to design efficient routes.

Most of the aforementioned data to design new routes are obtained from the routes that vehicles carried out previously and that are stored in the database of the waste management company. Unfortunately, the waste management company has no data about most of the distances and travel times in its database. This is because of the routes that include those collection points for which there are no historical travel times have never been designed. Additionally, there are travel times between points that are not reliable, updated, or contain errors. In order to solve the cases of lack or erroneous information, Google Maps Platform, and specifically its API Distance Matrix, have been used to compute and correct travel times.

Overall, it was essential to apply a correction factor and add the collection time of a container to the travel times between collection points. The correction factor has been obtained from the relation between a large sample of travel times stored in the database of the company route planning systems and the travel times provided by Google Maps Platform for the same pairs of points. This value indicates that vehicles use, in general terms, around 50% more time than those provided by the Google Distance Matrix API. As mentioned above, the collection time of containers have been added to the travel times. It is assumed that once the vehicle has stopped in front of the container, the time required to empty its contents in the vehicle and locate the container in the same place to continue the route is stable. In other words, this time is similar for all containers regardless of their content and location, among others. The values stored in the database of the waste management system and the information extracted from the interview phase with the agents responsible for the waste collection, establish a reasonable time of 120 s.

5.3. Designing routes

As indicated before, a new collection route must be designed at each step of the GRASP. With this goal in mind, we propose a flexible semi-greedy constructive method. Its pseudo-code is depicted in Algorithm 2.

Algorithm 2. Pseudo-code of the method used to build routes of the GRASP

```
Input  : v. Vehicle used in the route
         P(v). Set of waste collection points that can be collected by v
         κ. Size of the restricted candidate list
Output: r. Collection route of vehicle v
1  r ← (o(v), t(v))
2  while improvement do
3      while P(v) is not empty and constraints are satisfied do
4          Evaluate the candidate elements in P(v)
5          RCL ← Build the restricted candidate list
6          p ← Select an element from the RCL
7          Add waste collection point of p to route r
8          Update the set of candidate elements
9      end
10     Apply improvement strategy to r
11 end
12 return r
```

It receives the vehicle to be used in the route, the set of waste collection points that can be collected by it as well as the size of the restricted candidate list as input parameters. Each route is here defined as a sequence of waste collection points to be visited by the corresponding vehicle. The first step in the design process is to build a route, r, composed of the starting and ending locations for vehicle v and with no waste collection points (line 1). Then, the impact of each available waste collection point on the objective function value when included in each potential position of the route is evaluated (line 4). According to this evaluation, a restricted candidate list composed of those waste collection points and position in the route with the highest increment of the objective function value is built (line 5). This list is sorted by the increment of the objective function value, in such a way that those candidates with the highest increment have higher probability of being used to update the route. The size of this list is restricted by the parameter κ, whose value is set by the user. One of the candidates, p, in the restricted candidate list is selected by a roulette wheel selection (line 6). The corresponding point is added to the route under construction (line 7). Once the point has been added to the route, the set of candidate elements is updated (line 8). This process is repeated until no additional waste collection point can be added to the route while fulfilling the constraints imposed by the optimization problem (lines 3–9). It should be noted that, due to the maximum duration constraints of the route, some waste collection points cannot be included without exceeding this bound. These waste collection points are consequently ruled out from the selection process.

Moreover, the semi-greedy constructive method reports feasible solutions of the optimization problem under analysis. However, the quality of the routes could be enhanced by applying some improvement strategy. In this case, the Lin-Kernighan heuristic proposed for the Traveling Salesman Problem is used (Helsgaun, 2000). Applying this technique allows to reduce the distance traveled by the vehicle when visiting the sequence of waste collection points. This potential improvement enables to add new waste collection points to the route under construction (lines 2–11). Finally, the process is finished by returning the built route, r (line 12), when any improvement can be obtained.

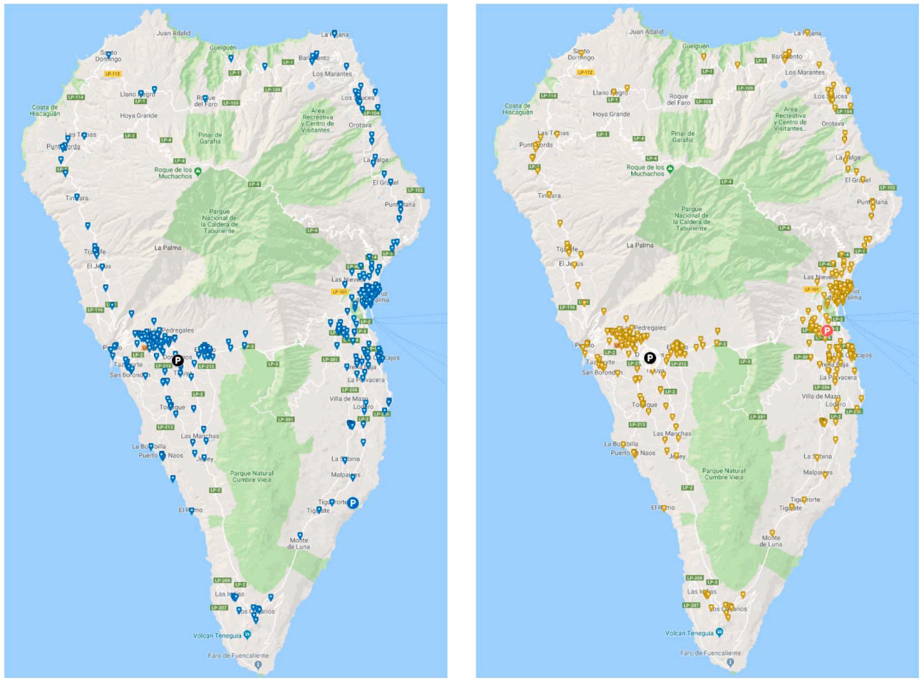
6. Computational results

This section is dedicated to present the computational experiments carried out in this work. The main objectives of the computational experiments are described as follows:

1. Evaluating the solution approach used to propose improvements on route planning for collection of recyclable waste from eco-efficient perspective.
2. Comparing the current routing scheme carried out in the past by the operator company to the results of the proposed optimization technique.
3. Analyzing several eco-efficient indicators that are of the interest for the waste management company.

The computational results referred to throughout this section were performed by a personal computer equipped with an Intel Core 2 Duo E8500 3.16 GHz and 4 GB of RAM. The solution approach was development using the Java SE 8.0 language. The computational time that the solution approach requires to solve the scenario under analysis stands at around 1 min. Notwithstanding, the computational times are not very relevant for the waste management company. This is partly due to the fact that the process of planning routes would be performed the night before the first day of the planning horizon. The stopping criterion used in the solution approach is defined based on the number of iterations. Hence, the search of solutions is repeated a certain number of iterations, specifically 10 iterations in the computational experiments carried out, and the best solution obtained after the defined number of iterations is returned.

The current section is split into the following subsections. Firstly,



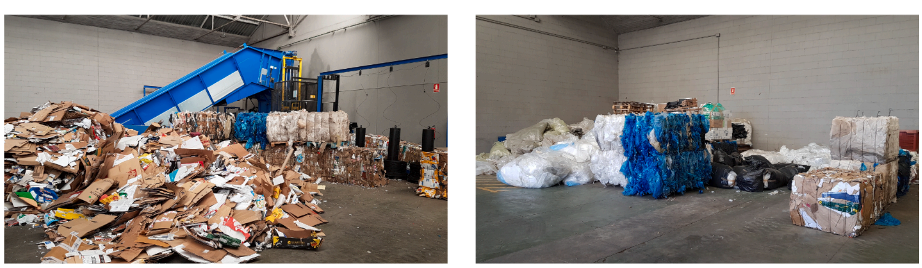
(a) Paper and cardboard packaging containers and waste processing plants
(b) Plastic packaging and cans containers and waste processing plants

Fig. 3. Containers and waste processing plants distribution in La Palma.

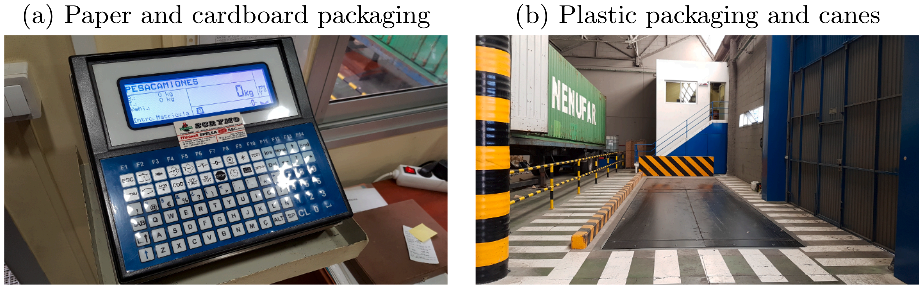
Section 6.1 introduces the characteristics of the geographical scenario in which the route planning is performed. Then, Section 6.2 describes the data used to design the real case instances addressed in this work, including the containers location, the distances and travel times between containers, and other relevant information. Finally, the analysis and comparison of the solutions provided by the proposed solution approach and the previous planning scenarios are presented in Section 6.4.

6.1. Scenario under analysis

It is necessary to describe the geographical context in which the project is developed in order to understand the particularities of the data cited above. The island of La Palma has an area of 708.32 km^2 and their territory is very rugged, reaching 2426 m. at Roque de los Muchachos, the highest point on the island. It is the second island with the highest altitude in the Canary Islands. Additionally, it is one of the Canary Islands with the largest forest area. The total population is 87,324 inhabitants. Around 25% of the total population of La Palma is in the municipality of Los Llanos de Aridane, and about 40% in El Valle de Aridane. The population is highly concentrated in two cities, Santa Cruz de La Palma (eastern side) and Los Llanos de Aridane (western side). In addition, La Palma registers a high level of unclassified population, which shows the number of tourists it receives annually. Concerning



(a) Paper and cardboard packaging
(b) Plastic packaging and canes



(c) Truck scale display
(d) Truck scale platform

Fig. 4. Waste recycling plant in the island of La Palma.

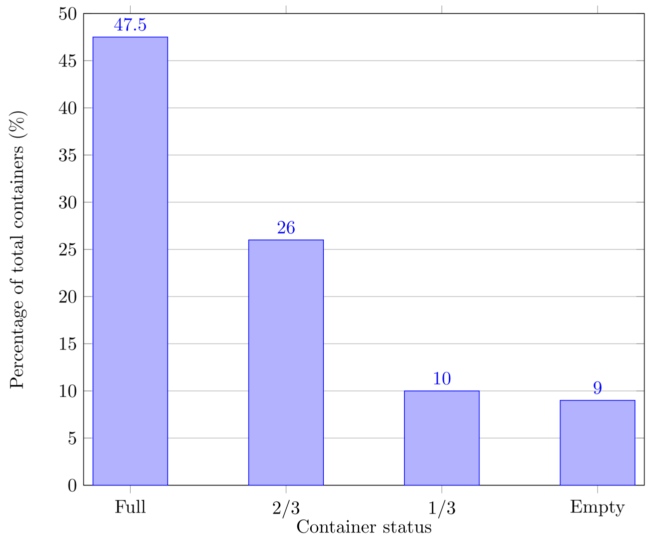


Fig. 5. Fill level of containers.

transport infrastructure, the roads of La Palma constitute a network of 510.06 km. Most of the roads are paved and in reasonable conditions, although practically all have many curves. The main roads are described below. The roads, LP-1 and the LP-2, compose the main ring road of La Palma with 157.88 km. The LP-3 road, with an extension of 25.9 km, is a mountain road that crosses the island from east to west passing through two excavated tunnels. A 47.84 km road, LP-4, ascends to the Roque de los Muchachos, going down the northern slope of the island. The LP-20, is a 3.70 km ring road that avoids the passage through the urban area of one of its cities with largest population, Santa Cruz de La Palma. The road network is completed with 47 more secondary roads.

6.2. Data summary

Most of the input data used in this work comes from the real case study in La Palma, Canary Islands, Spain. Therefore, a huge portion of the computational experiments input data are real data used in the application context of recycle waste collection described in this work. The main input data are related to containers location, ending/starting points as depots and waste processing plants, the distances and travel times between containers and vehicle operations, and the fill level of the containers.

The distribution of the containers across the island of La Palma is organized in collection points. The instance based on real data of the technology and research transfer project addressed has 774 containers distributed in 338 collection points. The containers can be split into 399 containers for recyclable plastic packaging waste and 375 containers for recyclable paper and cardboard waste. Fig. 3 shows the containers distribution around La Palma. The capacity of all containers is homogeneous, specifically 3000 l. Regarding the starting depots and waste processing plants, there are three known starting and ending points. In particular, there are three points whose locations are found in Breña Alta, Mazo, and Los Llanos, municipalities of La Palma. Fig. 4 shows one of the waste processing plants located in La Palma, specifically the two types of recyclable waste and the truck scale and its display respectively. The real data of the containers, collection points, and starting and ending points belonging the instances are taken from the private waste management platform of the operator company in charge of designing the routes and managing the resources used in them.

The other essential data set for the design of recyclable waste collection routes is composed of the costs or travel times of the vehicles and distance between the collection points, and starting and ending points. Hence, the cost data are structured in two square matrices, $M_d = (d_{ij})$ and $M_t = (t_{ij})$, relative to distances and times between collection points respectively. These matrices have size of $N \times N$, with N equivalent to the sum of the collection points number and starting and ending points with $1 \leqslant i, j \leqslant N$. Both matrices have the following characteristics:

- The entries in the main diagonal are all zero, $d_{ii} = 0$ and $t_{ii} = 0$ for all $1 \leqslant i, j \leqslant N$.
- All the off-diagonal entries are positive, $d_{ij} > 0$ and $d_{ij} > 0$, if $i \neq j$.
- The matrices are not symmetric, $d_{ij} \neq d_{ji}$ and $t_{ij} \neq t_{ji}$ for some $1 \leqslant i, j \leqslant N$.

Due to the complicated orography of the region with a rugged terrain and high altitudes, the road network presents abrupt changes in altitude with high inclines and many curves. This fact can be seen in the no direct proportion between entries d_{ij} and t_{ij} of the road distance matrix and travel times matrix, respectively.

Regarding the fill level of the containers, and as previously mentioned in Section 5, a function has been developed to estimate the fill level of the containers. However, in order to study the historical data available through the private waste management platform of the operator company, the routes carried out by the vehicles and the fill levels in the collection of the containers were analyzed. The relative percentages of times that a full container is collected is 50%, 25% for containers at 2/3 of its capacity, and 12,5% for containers at 1/3 of its capacity and vacuum. In other values, of every 8 container collected, 4 are full, 2 to 2/3 of its capacity, one to 1/3 of its capacity and another empty. The Fig. 5 illustrates the historical fill level of the containers.

Table 1
Summary of the comparison carried out between the mathematical model and the heuristic approach.

		Mathematical model		Heuristic solution	
		Paper	Plastic	Paper	Plastic
Day 0:	Pickup points visited:	122.00	112.00	81.00	75.00
	Containers visited:	173.00	158.00	115.00	111.00
	Total Distance (m.):	93102.00	99299.00	117429.00	141474.00
	Total Time (s):	23391.73	23397.79	23382.92	23382.22
	Fill Level (%):	77.05	61.81	90.44	71.27
Day 1:	Pickup points visited:	98.00	92.00	24.00	38.00
	Containers visited:	147.00	129.00	37.00	49.00
	Total Distance (m):	89629.00	142891.00	148410.00	152071.00
	Total Time (s):	23352.56	23383.54	23397.72	23388.41
	Fill Level (%):	49.84	39.16	88.51	66.77
Day 2:	Pickup points visited:	119.00	80.00	58.00	42.00
	Containers visited:	167.00	107.00	81.00	60.00
	Total Distance (m):	104786.00	121183.00	140483.00	152698.00
	Total Time (s.):	23367.76	23305.24	23389.38	23360.33
	Fill Level (%):	46.70	36.85	86.74	72.29
Day 3:	Pickup points visited:	103.00	93.00	83.00	58.00
	Containers visited:	148.00	131.00	103.00	79.00
	Total Distance (m.):	112359.00	113072.00	113375.00	136794.00
	Total Time (s):	23392.88	23335.64	23357.65	23397.78
	Fill Level (%):	45.10	46.76	87.53	66.86
Day 4:	Pickup points visited:	108.00	96.00	56.00	47.00
	Containers visited:	150.00	134.00	81.00	72.00
	Total Distance (m):	92495.00	146495.00	131091.00	150099.00
	Total Time (s):	23388.84	23395.02	23398.82	23385.59
	Fill Level (%):	50.01	41.27	84.33	75.166

6.3. Comparison of mathematical model and heuristic solution approach

The mathematical model proposed in this paper (Section 4) provides a mean to formally define the optimization problem under analysis without ambiguity. However, since the daily fill levels depend on the

Table 2
Summary of the comparison carried out between the proposed algorithmic approach and the current scenario during the first week of October.

Indicator	Proposed Scenario	Current Scenario
Routes	10	13
Time (h)	65	128.9
Time per route (h)	6.5	9.915
Distance (km)	1383.924	1162.534
Distance per route (km)	138.392	89.426
Containers	788	1215
Container by day	157.6	243
Overflowing containers	115	Unknown
Fill level (%)	78.995	61.113
Kilograms (kg)	15792.94	18563.074
Kilograms by hour (kg/h)	243.134	144.011
Consumption (l)	624.225	1238.729
Consumption by kilogram (l/kg)	0.040	0,067
Distance by kilogram (km/kg)	0,088	0,063
Time by kilogram (m/kg)	0,247	0.427

Table 3
Routes duration.

Week day	Month day	Operation time
Monday	October 2	12.985 h
Tuesday	October 3	15.470 h
Wednesday	October 4	10.290 h
Thursday	October 5	10.805 h
Friday	October 6	14.900 h
Average		**12.89** h

Table 4
Routes distance.

Week day	Month day	Historical distance	Solution distance
Monday	October 2	72.087 km	129.451 km
Tuesday	October 3	84.947 km	150.240 km
Wednesday	October 4	137.778 km	146.590 km
Thursday	October 5	80.204 km	125.084 km
Friday	October 6	85.156 km	140.595 km
	Average	**89.426** km	**138.392** km

Table 5
Number of collected containers.

Week day	Month day	Historical number	Solution number
Monday	October 2	242	226
Tuesday	October 3	304	86
Wednesday	October 4	145	141
Thursday	October 5	198	182
Friday	October 6	326	153
	Total	**1215**	**788**

containers collected the previous days, the mathematical optimization model is not a linear programming problem, and thus it cannot be implemented directly through MIP solvers such as IBM ILOG CPLEX.[3]

An alternative way of using the mathematical model is to consider only the reduced model corresponding to a single day. In this case, the fill level of the containers are known and the mathematical model is linear. Hence, the reduced model can be solved by CPLEX or any other MIP solver. Therefore, once the solution provided by CPLEX for the first day is obtained, the fill level of containers for the second day are updated, and CPLEX solves the problem for the second day. This process is repeated for the following days until the planning horizon is completed.

Accordingly, a small computational experimentation has been carried out to test this alternative solution approach with the reduced model formulation and it has been found that CPLEX has difficulties to provide high quality solution when the problem reaches the dimensions corresponding to the scenario presented in this work. This method has been applied to the real case analyzed in this work and the results show its deficiency. Table 1 describes the data of the comparison.

In the case of paper and cardboard waste collection, where the instance has 375 containers to collect, the results provided by CPLEX 12.9 for the planning horizon are worse than those provided by our heuristic solution approach. It can be seen that the fill level of the solutions obtained by CPLEX are considerably lower than those obtained by the heuristic solution approach. The maximum execution time used by CPLEX is two hours for each day of the planning horizon whereas the heuristic solution approach execution time requires around 1 min. As regards instance of plastic packaging waste collection, the number of containers reaches 399. The solutions provided by CPLEX using a maximum of 2 h of execution time per day of the planning horizon are worse than those obtained by the heuristic solution approach.

Table 6
Average fill level of containers collected.

Week day	Month day	Historical fill level	Solution fill level
Monday	October 2	69.588%	80.857%
Tuesday	October 3	62.228%	77.646%
Wednesday	October 4	53.594%	79.522%
Thursday	October 5	54.189%	77.203%
Friday	October 6	58.479%	79.749%
	Total	**61.113%**	**78.995%**

6.4. Analysis and solution comparison

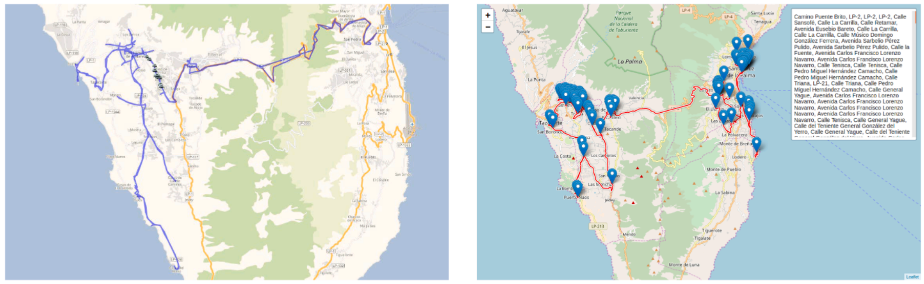
In this section, an analysis and solution comparison is carried out between the proposed solution approach and that implemented by the operator company along a given planning horizon. In order to perform the comparison, the route planning carried out by the operator company is extracted for a one-week planning horizon. Specifically, the first week of October, from Monday 2 to Friday 6.

Another relevant input information refers to the moment of the last containers collection at the time of planning the routes in the beginning of the planning horizon. The objective is to take into account the precise time during which each container has been collecting recyclable waste deposited. This information is obtained from the private waste management platform of the operator company that indicates the days that have passed since the last collection of each container until the beginning of the planning horizon. If this information is not available, in order to determine the initial value of the number of days a container has not been collected, we use the information that contains the containers and the last day of the week in which they usually are collected. Based on this information, the days until the day before the beginning of the planning horizon are counted.

Regarding to the characteristics of the available vehicles fleet, some important data are the number of vehicles, type of recyclable waste that can collect and capacity of each vehicle. It is assumed that, for practical purposes, vehicles have unlimited capacity since in case of operating the maximum time allowed and collecting full containers there would be sufficient capacity. Additionally, there are two vehicles for each day of the planning horizon, one for each type of recyclable waste.

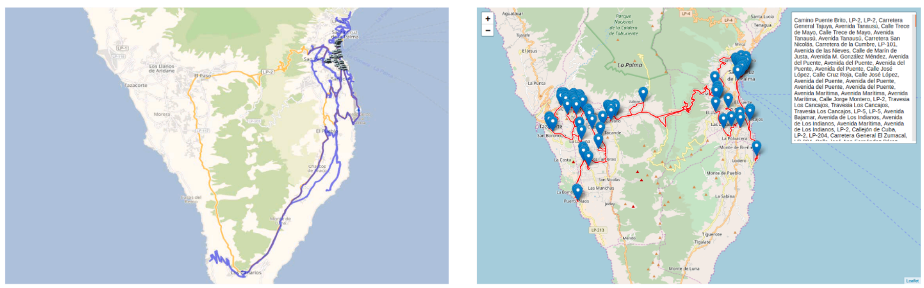
The comparative results are shown for the week of October 2–6,

[3] https://www.ibm.com/analytics/cplex-optimizer.



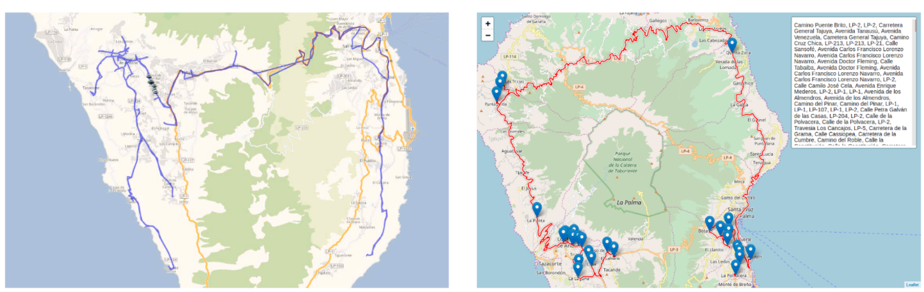
(a) Historical solution (b) Proposed solution

Fig. 6. Monday, October 2. Paper and cardboard packaging.



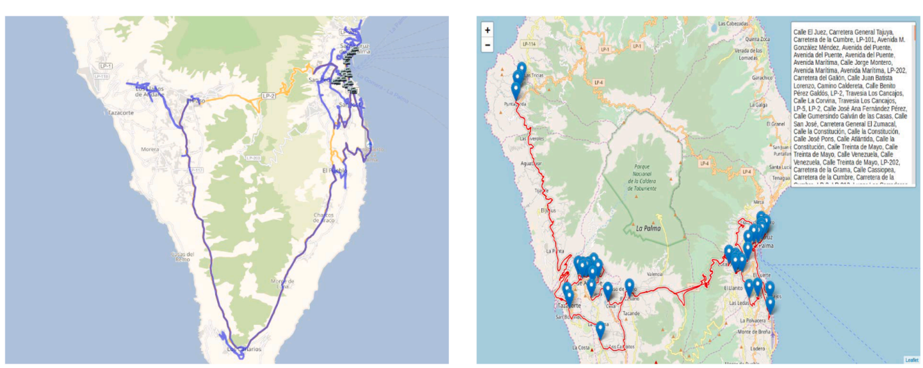
(a) Historical solution (b) Proposed solution

Fig. 7. Monday, October 2. Plastic packaging and cans.



(a) Historical solution (b) Proposed solution

Fig. 8. Tuesday, October 3. Paper and cardboard packaging.

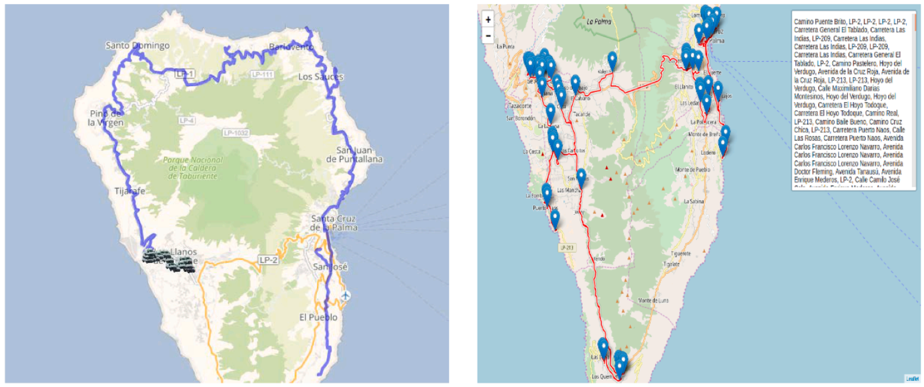


(a) Historical solution (b) Proposed solution

Fig. 9. Tuesday, October 3. Plastic packaging and cans.

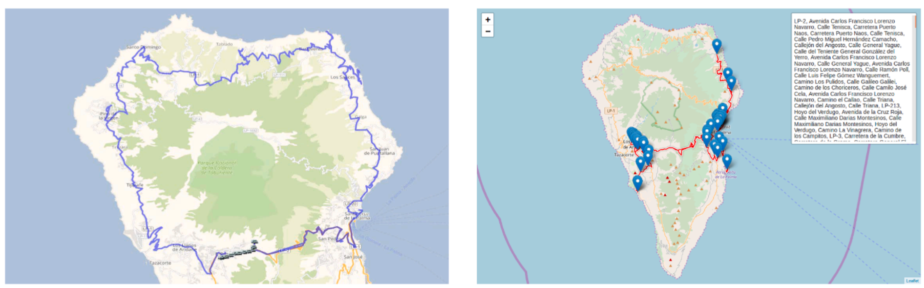
which is a week without holidays on La Palma and whose previous week does not have holidays either, in order to avoid that special circumstances may affect the comparison in a decisive way. The comparison is carried out with the results of the route planning carried out by the operator company as it is reflected in their private waste management platform. The maximum working time is set to 6,5 h per route.

The global indicators that summarizes the computational results achieved by the solution approach introduced in Section 5 and the selected route planning carried out by the operator company on first



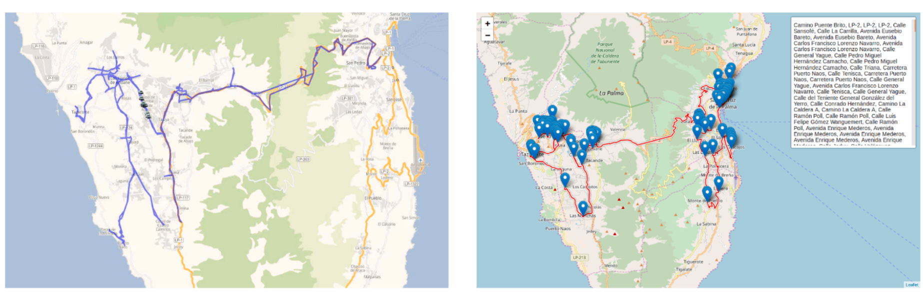
(a) Historical solution (b) Proposed solution

Fig. 10. Wednesday, October 4. Paper and cardboard packaging.



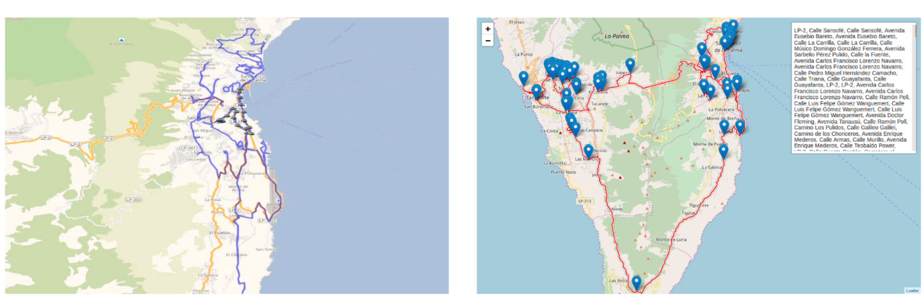
(a) Historical solution (b) Proposed solution

Fig. 11. Wednesday, October 4. Plastic packaging and cans.



(a) Historical solution (b) Proposed solution

Fig. 12. Thursday, October 5. Paper and cardboard packaging.

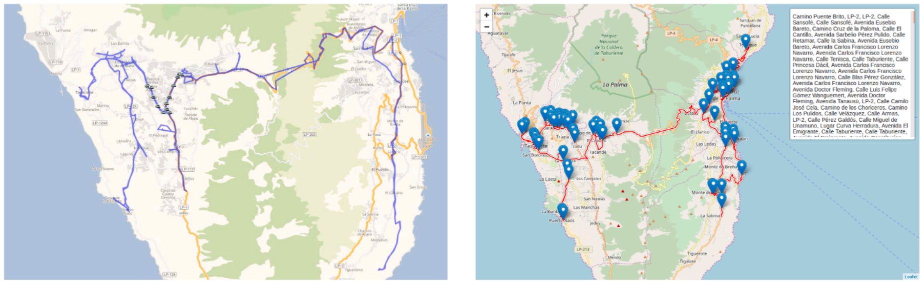


(a) Historical solution (b) Proposed solution

Fig. 13. Thursday, October 5. Plastic packaging and cans.

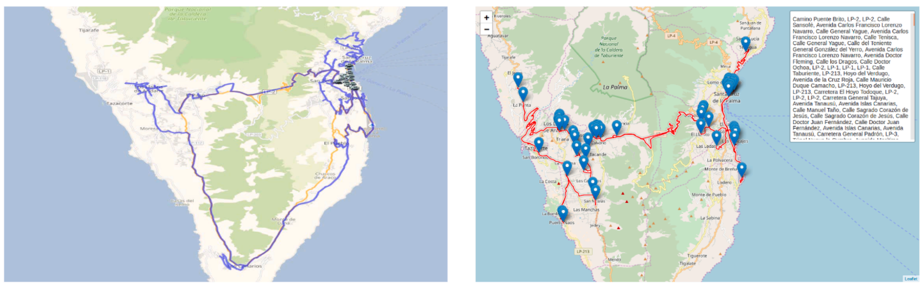
October week, are described in the Table 2.

The summary table shows indicators related to logistics aspects and environmental impact of route planning for collection of recyclable waste. The indicators presented are widely used by the national waste management company to evaluate the actions of recyclable waste collection throughout the country. Three groups are established to differentiate and group the presented indicators. The first group consists of indicators related to distance, duration, and number of routes to be



(a) Historical solution (b) Proposed solution

Fig. 14. Friday, October 6. Paper and cardboard packaging.



(a) Historical solution (b) Proposed solution

Fig. 15. Friday, October 6. Plastic packaging and cans.

carried out. Consequently, the second group contains indicators related to the fill level and the number of containers collected. The environmental impact of the recycling process is included in the last group of indicators. The time and distance required to collect one kilogram of recyclable waste, the amount of recyclable waste collected, and fuel consumption are some of the indicators collected in the last group.

In Table 2, it can be seen that the use of the solution approach described in Section 5 allows to improve a large part of the indicators used by the national waste management company to evaluate the actions of collecting recyclable waste. The maximum duration of each route carried out by a vehicle each day is 6.5 h. This requirement was established by the waste management company in order to study the feasibility of collecting the containers within a working day of a driver per vehicle. Assuming a normal working day of 8 h, the remaining 1.5 h are covered by possible unexpected events (*e.g.*, weather conditions, traffic jams, etc.) and rest periods.

Currently, the waste management company makes use of more than 10 routes during a week (*e.g.*, 13 routes in the current analysis comparison). Consequently, this requires a high amount of working hours. As a result, the requirement of reduce maximum duration seeks to reduce labor costs in the medium term. Regarding to the current case, a total of 128.9 h instead of 65 h proposed by the solution approach. Nonetheless, the distance traveled by the vehicles is increased due to the working hours reduction. This fact is motivated by the strategy that exists in the selection of the collection points used by the meta-heuristics. More specifically, the containers collected are those with the highest fill level, regardless of distance to which they are located.

Additionally, the fill level of the containers is better in the proposed solution (78.995% compared to 61.113%), notwithstanding the reduction in time and number of routes to be carried out. According to the comparative data, vehicles increase their productivity during the collection process. Regarding the amount of recyclable waste collected, the proposed solution is nearly equivalent to the routes planning the operator company, however, the time required and the fuel consumption of the vehicles to collect the recyclable waste is significantly reduced. These data describe a reduction of the environmental impact that is especially important for national waste management company.

The Tables 3–6 present the data of the comparison according to each day of the week for the selected planning horizon.

Figs. 6–15 show several examples of the routes obtained by the proposed solution approach for the selected planning horizon in comparison with the route planning proposed by the operator company. The figures shows that the proposed route planning have larger routes and lower number of containers collected across La Palma. Nonetheless, the mechanism of selecting the most convenient containers to collect increases the amount of recyclable waste in each collection, increasing the distance traveled by the vehicles.

7. Conclusions and further research

This paper proposes a solution approach to solve a hard waste collection problem in La Palma (Spain). In light of the implementation and results derived from the project, it has to be firstly emphasized that the existing data about the whole waste management process is a major asset, both for waste management and operator companies. In this regard, one of the fundamental advantages associated with data availability is the possibility of evaluating multiple collection strategies. The main objective of evaluating strategies from the data is to select the best options in decision making processes. At the same time, as a consequence of the evaluation processes of alternatives or decision support, new opportunities are opened to focus the activities. In fact, the processes of evaluation of alternatives and optimization of decisions based on a continuous data update allow converting decision making into a process of continuous performance improvement.

As demonstrated in the computational experiments, the availability of data allows to design efficient optimization techniques to solve the optimization problem under analysis. In this regard, we propose a technique based on the general framework of Greedy Randomized Adaptive Search Procedure. It firstly carries out a container selection strategy that obeys the main optimization objective: maximizing the fill level of the collected containers. For this purpose, the containers with the best estimated fill level are selected. Subsequently, an improvement strategy is used to reduce the travel time of the routes, which allows to insert new containers. The selection of containers can be modulated to meet other types of criteria. The most direct effect of the use of these smart strategies is to obtain a cost reduction to achieve equivalent or better performance levels in the selective collection. As a result of the optimization of the collection routes, an improvement in the different environmental indicators is obtained by reducing the operating time, fuel consumption, and emissions produced by the vehicles while the levels of collection are maintained and even improved. As a final result, a higher quality in the service delivery is achieved as the collection is more efficient and effective, and in an indirect way it can meet other criteria without reducing the overall performance.

Moreover, a very relevant aspect of the proposed solution approach is its great adaptability to tackle new optimization criteria and constraints. The technique offers a variety of alternatives that meet the applied criteria and imposed requirements but that differ in other collateral aspects. This allows to make decisions based on relevant characteristics of the proposals that have not been initially imposed. Furthermore, the technique takes advantage of the available information at any time to allow a dynamic behavior adapting his response to the changes that are detected while the collection process occurs. Therefore, the changes in the context that are reflected in the updates of the input data are directly assumed by the solution approach to adapt its proposal. Also, adding new requirements is done automatically by adapting the container selection criteria and the evaluation of the route improvement movements, giving rise to high quality proposals respecting the constraints. At the same time, the particularities of the proposed approach allow its easy and effective integration with other technological tools to take advantage of the dynamic information, and thus quickly provide solutions that can be applied directly. Lastly, this high adaptability of the developed solution approach allows the extrapolation of its good performance to other territories where the requirements and applicable criteria have different characteristics.

On the basis of the contributions presented in this paper, several promising lines are still open for further research. The waste management company provides special service to several social and sporting events in the island throughout the year. These require the deployment and collection of a set of temporary containers aimed at fulfilling the demand generated by the events. The changes in the availability of resources, traffic flows, etc. are still an open problem to be analyzed and solved by the company. Also, the waste management company is interested in reducing the impact of the collection process on the rest of the residents and tourists as well as on helping to other public services. For this reason, it requires to consider time slots to collect certain containers in the middle term. Lastly, the operator company is highly interested on integrating the information about fuel prices and location of fuel station in the design of the collection routes, in such a way that the fuel consumption will be eventually minimized.

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Appendix A. Notations

$\mathcal{G}$	Graph
Θ	Set of nodes in G
A	Set of arcs in G
H	Planning horizon, expressed in number of days
E	Set of start and end points
$\mathcal{V}$	Set of collection vehicles
k	Number of vehicles
m	Number of waste collection points
n	Number of locations
r	Number of start and end locations
$o(v)$	Origin location of vehicle $v \in \mathcal{V}$
$t(v)$	Target location of vehicle $v \in \mathcal{V}$
$l(i)$	Number of containers in the waste collection point $i \in P$
P	Set of waste collection points
P_i	Set of containers in waste collection point i
$P(k)$	Set of waste collection points that can be collected by vehicle $k \in \{1, 2, ..., K\}$
c_j^i	Container j that belongs to waste collection point $i \in P$
C	Set of containers
$f(c, h)$	Fill level of container $c \in C$ since h days from the last collection
$q(c)$	Fill rate of container $c \in C$
$b(c)$	Fill level of the container $c \in C$ after collected
$f_i(h)$	Fill level of waste collection point $i \in P$ since h days from the last collection
$s(c)$	Collection time of container $c \in C$
s_i	Collection time of the containers found in location $i \in V$
t_{ij}	Travel time between waste collection point i and j
d_{ij}	Distance between waste collection point i and j
W_{kd}	Maximum working time of vehicle $k \in \{1, 2, ..., K\}$ in day $d \in \{1, 2, ..., H\}$
$\mathcal{D}_{ih}$	Set of days in the planning horizon in which the collection point $i \in P$ has been collected before day $h \in \{1, 2, ..., H\}$
η_{ih}	Number of days since the last collection of the point $i \in P$ in day $h = \{1, 2, ..., H\}$
M	Big constant

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