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Optimization in a Waste Management System:

Integration of Domestic Organic Waste Collection in Lisbon

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A B S T R A C T

Currently, at least 33% of Municipal Solid Waste (MSW) generated worldwide is still burned or dumped in landfills, leading to the release of methane resulting from the decomposition of organic waste, which contributes to global warming (Kaza et al., 2018). In order to improve the situation and build sustainable cities the European Union has launched a campaign that accounted Lisbon for the collection of 4000 tonnes of organic waste in the domestic sector.

This dissertation aims to incorporate and optimize domestic organic waste collection into the Municipal Solid Waste Management System (MSWMS) of Lisbon. A set of collection points to introduce the new waste flow is given, to which current collection operations have to be assigned and vehicles routes have to be designed. To do so, several modifications in the MSWMS have to be applied, so that the problem takes into account two main concerns: one of organizational character related with the simplicity with which the solution is to be implemented, other of economic character linked to the resulting additional costs.

Consequently, an approach was developed to deal with several aspects of the problem. Three scenarios regarding how the new waste flow will be incorporated were proposed and analised, and a model combining TSP and MDVRP heuristic procedures was developed to route the vehicles. Due to multiple aspects in each scenario, the model developed must be flexible enough to cope with all of them while optimising distance and time. In the end, a comparison between scenarios will be performed.

KEYWORDS: Waste Management; Waste Collection; Organic Waste; Vehicle Routing Problem.

1. Introduction

In 2016, approximately 2.01 million tons of municipal waste were generated, which, due to their mismanagement, contributed to global warming with greenhouse gas emissions effect equivalent to 1.6 million tons of carbon dioxide. Currently, at least 33% is still landfilled or burned. The major contribution is the release of methane from decomposition of organic waste (Kaza, Yao, Bhada-Tata, & Woerden, 2018).

In order to build sustainable cities, the study of Waste Management (WM) discipline is crucial. This is a multidisciplinary activity that includes a range of strategic, tactical and operational decisions combining a large number of activities. With population growth, limited vehicles and increased traffic, waste collection and transport component are an increasingly complex and time-consuming task.

Efforts to formalize WM can reduce greenhouse gas emissions. Thus, the European Union launched several campaigns to this end and Lisbon was accounted for collecting and treating over 7000 tons of organic waste, of which 4000 in the domestic sector.

In short, this study is born due to the environmental risks caused by waste, the complexity of waste management and collection and the European campaign for the city of Lisbon.

Ultimately, it aims to introduce the collection of 4000 tons of organic waste into the Municipal Solid Waste Management System (MSWMS) of Lisbon considering two main concerns. One of organizational character related with the simplicity with which the solution is to be implemented in a real situation. Other of economic character, linked the additional costs triggered by the organic waste collection introduction in the MSWMS. In one way or another, both aspects are related with efficient routing of collection vehicles.

Generally, when solving WM route optimization problems, a map containing the starting location of vehicles, waste collection points and disposal sites is provided. This map can be transformed into a network with a set of vertices and branches. As routing will be performed over the nodes, this problem can be modelled as a Vehicle Routing Problem (VRP) with some modifications to deal with specific particularities and constraints of the problem.

VRP is a generic designation for a class of problems that is concerned with constructing routes for a fleet of vehicles that want to visit a set of locations, subject to a set of constraints (Laporte, 2009). It was first introduced as the Truck Dispatching Problem by Dantzig & Ramser (1959), and first applied to waste collection problems by Beltrami & Bodin (1974). VRP is a natural extension of the Travelling Salesman Problem (TSP), to which a level of decision is added.

The city of Lisbon, as a capital and an attractive hub of goods, people and services, stands out nationally for the high quantities of valuable materials that are produced. According to producers' type, urban morphology and socioeconomic characteristics of each area, there are several disposal and collection solutions. Organic waste flow can be incorporated with Door-to-door selective waste collection in domestic sector by modifying the current weekly calendar in order to include organic waste days. It also can be incorporated with Door-to-door organic waste collection in the commercial sector.

To solve this problem, a set of collection points to install new organic waste containers is given and several decisions have to be made regarding how they will be collected. In this paper the focus is in which current operations will be used to collect new collection points, and routing and scheduling of vehicles to visit them. Other restrictions will not be considered.

In our approach, the problem is simplified by considering three distinct scenarios and then we develop a model combining TSP and MDVRP heuristic procedures to route the vehicles in each scenario. The model considers several aspects of the problem, such as freights to unload the collected waste, and different treatment stations depending on waste flows being collected.

According to the context of the problem and its methodology, the main objectives of this paper are: (i) characterization of the problem and the case study, (ii) review of the main models and methods used to solve WM problems, (iii) designing a model to incorporate organic waste collection into Lisbon's MSWMS, taking into account system mandatory constraints, execution simplicity and additional costs, (iv) create and implement in R programming language a routing algorithm based on heuristic procedures, (v) find the optimal route configuration for each scenario, providing viable decision options, and finally (vi) the evaluation of the solutions found to support the decision to launch the pilot project for the collection of organic waste in domestic sector.

Considering the methodology and given objectives, the paper proceeds as follows. Section 2 reviews and summarises relevant concepts and possible procedures in order to solve this problem. Section 3 describes the method employed to approach the aforementioned problem, the analysed scenarios and the developed models to solve them. Section 4 provides obtained results and a scenario assessment analysis is carried out, including advantages and disadvantages of each one taking into consideration the previously mentioned organizational factors of the problem. Finally, in Section 5 conclusions are summarised and future work is proposed.

2. Literature Review

2.1 Waste Management

Waste Management is a complex discipline that involves several decisions with multiple environmental and socioeconomic criteria. To design a sustainable Municipal Solid Waste Management System (MSWMS), stakeholders must set objectives and strategies so that decisions can converge in one direction (Soltani et al., 2015). The use of Operational Research (OR) techniques, such as modelling and optimization, are essential in decision support, cost reduction and performance improvements (Pires et al., 2018). In this context, decisions can be classified into strategic, tactical and operational (Ghiani et al., 2014). In the strategic domain we have all decisions that have long-lasting effects and high financial costs such as selection of treatment technologies, defining the location and capacity of transfer and treatment facilities, future expansions strategies and economies of scale. The tactical domain encompasses medium-term decisions such as waste flow allocation to treatment plants and landfills, division of territory into service zones and fleet composition. As for the operational domain, we can include all decisions with short-term impact, for example routing and scheduling of collection vehicles.

In this paper we study a practical case of waste collection in the MSWMS of Lisbon that includes tactical and operational decisions. A set of collection points is given and at a tactical level, it must be decided how they will be incorporated into the current system. Introducing a new set of collection points with a new waste flow leads to modifications in the current MSWMS and new routes have to be established at an operational level. Hence, optimizing the routes of collection vehicles becomes crucial.

2.2 Waste Collection

Waste collection is an important process of WM. It is defined as the collection and transport of waste to the place of treatment or discharge by municipal services or similar institutions. Collection of municipal waste may be selective, when carried out for a specific waste flow, or undifferentiated, when covering all waste flows at the same time (Han & Cueto, 2015). It was first presented by Beltrami & Bodin (1974).

Generally, when solving WM route optimization problems, a map containing the starting location of vehicles, waste collection points and disposal sites is provided. This map can be transformed into a network with a set of vertices and branches. When routing is performed over branches, waste collection can be described as an Arc Routing Problem such as the Chinese Postman Problem (Eiselt, Gendreau, & Laporte, 1995a) and the Rural Postman Problem (Eiselt, Gendreau, & Laporte, 1995b). These approaches are mostly used when urban collection is performed at various points along streets, in snow clearance or street sweeping.

In turn, when routing is performed over nodes, it can be described as a node routing problem. The most basic is the Travelling Salesman Problem (TSP) in which a vehicle must visit all nodes of a graph at the lowest possible cost, either time or distance (Flood, 1956). One of the most popular generalizations of TSP is the Vehicle Routing Problem (VRP). In the present study, the problem involves the collection and transport of waste in an urban area, but the places to visit are scattered and not found along streets. Thus, it becomes more appropriate to study Node Routing problems.

2.3 Vehicle Routing Problem

Vehicle Routing Problem (VRP) can be described as an optimal route design problem for a set of geographically dispersed customers - collection points - to visit from a source - depot - and subject to a set of constraints (Laporte, 2009). Since the problem implies that there is more than one vehicle, the objectives are to define the set of customers to serve and to find the lowest cost route for each vehicle. Thus, VRP is a natural extension of TSP, to which a level of decision is added. It was first introduced by Dantzig & Ramser (1959) under the name "The Truck Dispatching Problem" when they modelled a fleet of homogeneous vehicles that intended to serve a set of petrol stations from a depot. The state of the art regarding VRP, including its variants, already justifies taxonomic reviews (Braekers, Ramaekers, & Van Nieuwenhuyse, 2016; Eksioglu, Vural, & Reisman, 2009). To solve VRP problems, there are several algorithms available in the literature. For extent reviews see, for example, the works of Gendreau, Laporte, & Potvin (2011), Gilbert & Osman (1995) and Laporte (1992).

VRP algorithms are typically classified into Exact Methods, Classical Heuristics, and Metaheuristics (Laporte, 2009).

Exact Methods

Exact algorithms are designed to produce optimal solutions. They can be classified into three main categories according to Nobert & Laporte (1987): Direct Tree Search, Dynamic Programming, and Integer Linear Programming. Currently, TSP problems with thousands of nodes can already be solved (Applegate et al., 2009). However, as a TSP generalization, VRP is much harder to solve. Baldacci, Christofides & Mingozzi (2008) and Fukasawa et al. (2006) developed exact algorithms capable of solving instances up to 135 clients. More recently Pecin et al. (2017) solved some issues with 360 customers. Practical applications of VRP often exceed this dimension, hence most of the algorithms used in practice are heuristics and metaheuristics. Its popularity has increased in recent years leading to the development of a great diversity of algorithms.

Classical Heuristics

Classical Heuristics are approximate algorithms that do not allow the deterioration of intermediate solutions during the solving process (Laporte, 2009). According to Cordeau et al. (2007), we can classify them into two main categories: cluster first – route second (Gillet & Miller, 1974; Wren & Holliday, 1972) and route first – cluster second (Beasley, 1983; Bertsimas & Simchi-Levi, 1996). Besides this categories, classic heuristics are usually focused on construction and improvement procedures. Constructive heuristics typically start from an empty or infeasible solution, and build the solution by adding one node at a time or joining partial routes, according to some criterion. The most popular example is the savings methods introduced by Clarke & Wright (1964). Local improvement heuristics start with feasible solutions and iteratively apply simple modifications to the route structure in search of better solutions. These algorithms are generally used to improve solutions generated by other methods. Some examples include the methods of Lin (1965) and Lin & Kernighan (1973).

Metaheuristics

Metaheuristics are essentially local improvement algorithms that seek to find better solutions, but unlike classic heuristics, they admit temporarily degrading the quality of the solution to avoid being “stuck” on local optima. They intensively explore the most promising regions of the solution space and use sophisticated neighbourhood search techniques, memory structures, and solution recombination. Metaheuristics can be divided into three classes: local search, evolutionary algorithms and learning mechanisms (Laporte, 2009).

According to Cordeau et al. (2002) heuristic techniques should be evaluated in four criteria: precision, speed, simplicity, and flexibility. In general terms, metaheuristics produce better results, but with increasing complexity and longer calculation times. On the other side, classical heuristics stand out for their simplicity of comprehension and implementation, speed in obtaining results, and adaptability to VRP variants. Most techniques used in real cases are combinations of the various algorithms at different problem solving steps.

3. Lisbon’s Organic Waste Problem

The city of Lisbon, as a capital and attractive hub of goods, people and services, stands out nationally for the high quantities of valuable materials that are produced. Following recent European Union initiatives, Lisbon Municipality is now accounted for collecting and treating over 7000 tons of organic waste, of which 4000 in the domestic sector. Therefore, a new specific waste flow has to be inserted in Lisbon’s MSWMS and combined with current operations.

In this study, collection points are geographical locations that concentrate one or more containers destined to the same waste flow. These are arranged by circuits, which in turn is a set of collection points with the same waste flow intended to be visited during the same operators work shift and in which the same type of operation is executed. Since an operation involves different types of vehicles, containers, waste streams, calendars, and other constraints, it is necessary to understand in which one organic waste collection fits best.

To this end, a set of collection points to install new organic waste containers in residential buildings is provided and several decisions have to be made regarding how they will be collected, such as which current operations will be executed and which routes vehicles should proceed to visit them. We will designate these set of collection points by pilot project.

Two operations in this MSWMS were identified as feasible alternatives to insert the pilot project. Door-to-door selective waste collection in domestic sector by modifying the current weekly calendar in order to include organic waste days and door-to-door organic waste collection in the commercial sector by adding the new collection points to circuits executing this operation. Both options have different ways to interpolate with the MSWMS and will motivate modifications in the existing circuits that must be considered. Thus, in order to simplify the problem, it is necessary to previously define how and with which operations the pilot project should be integrated. To every affected circuit, routes must be designed. It should also be noted that the main objective of this study is not to improve the MSWMS as a whole, nor to isolate and optimise one future organics collection circuit. Rather, it is to minimise the impact of introducing organic waste collection into the system, that is, to minimise the costs of the altered circuits themselves, as well as the costs of the required changes to articulate with the system, without compromising its proper operation.

To conclude, the problem consists in deciding how the pilot project will be integrated in Lisbon’s MSWMS, with which operations, and by which routes. Given the difficulties arising from the various decision levels involved, our approach is to propose several scenarios and use a VRP model to each one of them in order to redesign the affected circuits, route the collection vehicles and complement an analysis of scenarios advantages and disadvantages with quantitative evaluation.

4. The Proposed Approach

To solve this problem we propose an integrated approach consisting in two main steps. To deal with several decision dimensions, the problem will be restricted into three scenarios describing how the pilot project can be inserted in Lisbon’s MSWMS. Each scenario has to be analysed and compared, ideally with quantitative measures. Routing the collection vehicles in each scenario will result in a total system distance for each one and thus reflecting the costs associated with that option. Therefore, the second and most important step of the proposed approach consists in the development of a flexible heuristic model to solve the routing problem in each scenario.

4.1 Scenarios of Analysis

The pilot project will entail modifications in the existing circuits and operations, hence three scenarios of analysis were defined. Figure 1 illustrates a representative scheme of present situation each scenario modifications.

In the present situation we consider the current circuits that either encompass the pilot project collection points or share the same waste flow. In this sense, there are four circuits of interest operating in door-to-door domestic selective waste collection, and seven circuits of interest operating in door-to-door commercial organic waste collection. Each scenario of analysis describes a way in which the pilot project can be inserted in the MSWMS, considering circuits reconfigurations and merges, and periodic calendar adjustments.

Note that although the pilot project can be interpolated with commercial organic waste collection, it will always be somehow connected with domestic selective waste collection in a periodic sense. Because organic waste will be collected in domestic sector, calendar adjustments are mandatory, and organic collection in the project pilot collection points will be executed in the same days as undifferentiated waste collection in non-pilot project collection points, according to the current and future calendar. This will have implications when analysing final results.

Scenario A

A particular circuit for the project pilot is defined. Remaining collection points will suffer arrangements and circuits modifications in accordance. The two most affected original circuits will be merged. The other two will suffer only slightly adjustments. In this scenario, collection will be performed in door-to-door selective waste collection.

Scenario B

Original circuits will undergo minimal changes in their configuration. Two circuits will include both organic and undifferentiated collection points. Those are mixed circuits. Since vehicles do not have the capacity to transport different materials at the same time, as they are not multi-compartmented, mixed circuits will have to perform a minimum of two freights, one for each type of waste. In this scenario, collection will also be performed in door-to-door selective waste collection

Scenario C

Circuits that collect organics in commercial entities will be reconfigured to include the organic collection points from the pilot project in their journey. Collection will be performed in door-to-door organic waste collection in commercial sector. Note that commercial organic waste collection circuits are not directly affected when inserting the pilot project since they commercial entities instead of residences. However, they share the same waste flow, and therefore provide an opportunity to take advantage of the available resources.

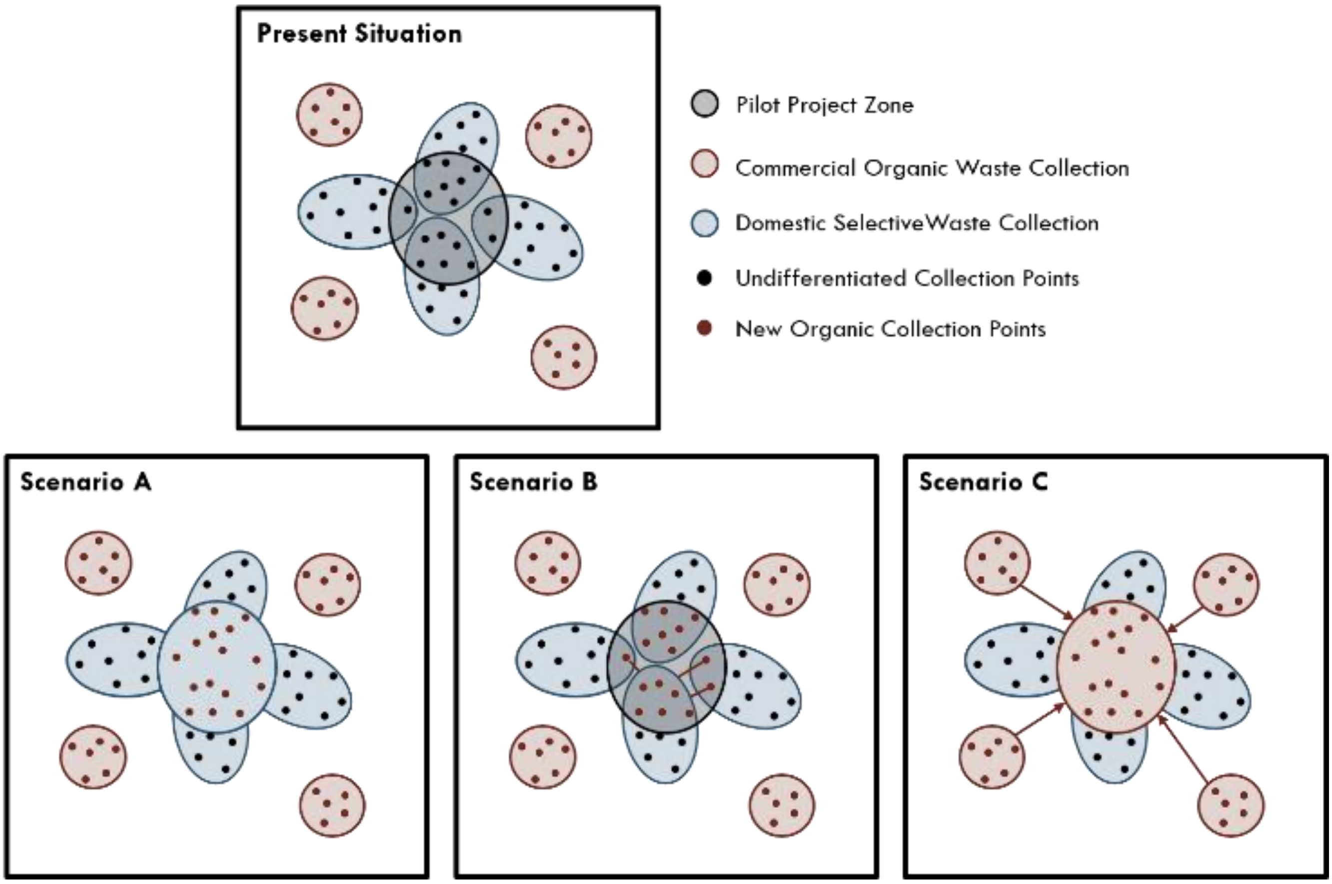

Figure 1- Scenarios Illustration

4.2 The Heuristic Procedure Applied

Due to multiple aspects concerning each scenario, the developed model must be flexible enough to cope with all of them while optimising distance and time. With flexibility in mind, the proposed heuristic will be partitioned into several procedures, designated in this study by modules. This modules are the main building blocks of the heuristic proposed in this study.

The undergoing problem has two concerns that must be considered: (i) Before returning to depot, the load must be dumped at the respective waste treatment facility, implying this as the next-to-last visit point on the circuit and that the arc between treatment facility and depot is always travelled. (ii) The frequent need for unloading freights implies extraordinary visits to treatment plants to restore vehicle capacity. To address these difficulties, routing problem was designed in two sequential phases, Construction Module to produce an Hamiltonian cycle with collection points and Metamorphosis Module to transform the cycle considering the aforementioned concerns. This approach grants the necessary flexibility to adapt the routing problem according to waste flow being collected when discharge freights are calculated and inserted into the circuit. Regarding Scenario C, a very simplistic approach based on Multi-Depot Vehicle Routing Problem (MDVRP) model has been adopted to design Evaluation and Allocation Modules. The strategy is to reduce the organic circuits to their mass center and treat them as depots. After modules description, the way they interact to produce final procedures for each scenario is also presented.

Construction Module

In the first two modules the goal is to build routes for a given circuit. In Construction Module, an Hamiltonian cycle will be constructed only for the collection points. We are thus facing a TSP. This procedure considers four heuristics: (i) nearest insertion, (ii) arbitrary insertion, (iii) cheapest insertion and (iv) farthest insertion. Each of these methods is applied to produce a closed loop visiting all collection points of one circuit. The best solution is selected.

Note that closed loops produced are usually different due to the random nature of the algorithms used, hence having implications in the following modules. Furthermore, the end result of this module will be a closed loop containing only collection points, thus having no consideration for capacity and time constraints. Finally, depot and treatment facility will not be considered as this would have consequences when using TSP algorithms, regarding issues with the fixed arc connecting treatment facility and depot. Therefore, the next module was developed to face these constraints.

Metamorphosis Module

This module transforms the closed loop produced in the previous module into a complete circuit considering the final journey between treatment facility and depot, and capacity constraints with the addition of unloading freights. Briefly:

1. Selects the first place to visit within the closed loop. Two different criteria will be used for the resolution of this phase; (i) Proximity criterion, based on nearest neighbour heuristic, in which the closest collection point from the depot is selected as the first to visit in the circuit. (ii) Savings criterion, based on Clarke & Wright (1964) algorithm, which consists in eliminating the arc with greatest savings potential, thus selecting the first collection point to visit. Because both criterions will be considered, the following steps will be working over the two distinct circuits produced.

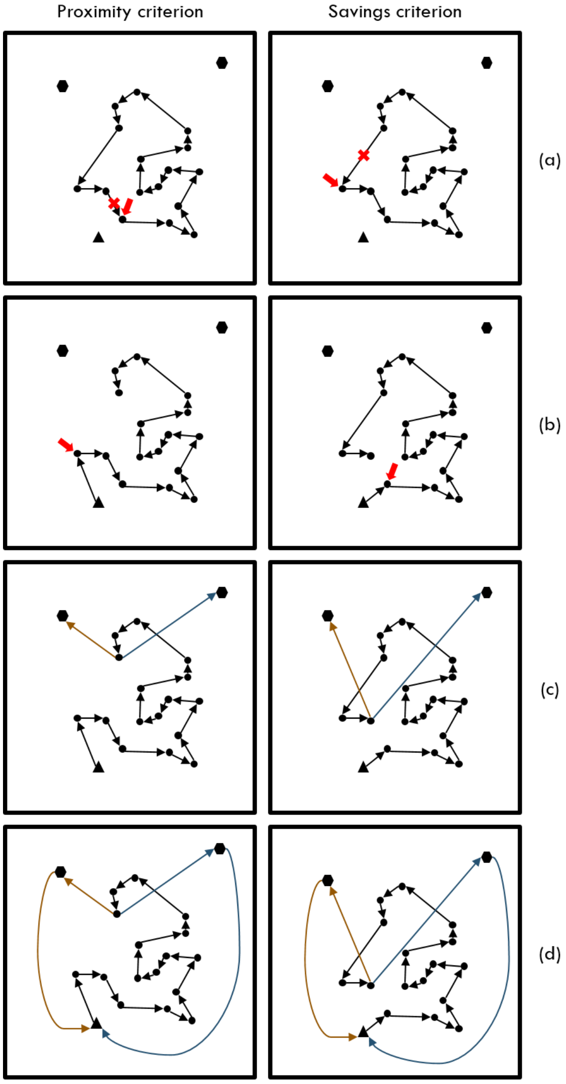

Figure 2 - Metamophosis Step 1 and 2

2. First resolution triggers two automatic consequences. Definition of the route order (a) and elimination of the arc between last and first collection points (b). Additionally, the last point is connected to respective treatment station (c) and the arc connecting respective waste treatment plant and depot is added (d). This steps are illustrated in Figure 2 together with first collection point selection criterions.

Note that each waste flow considered in the study has different treatment facilities, restricting this step to the waste flow being collected.

3. After defining the route order and knowing the amount of waste produced at each location, the vehicle capacity constraint is considered. The accumulated load on the vehicle is calculated at each collection point. Whenever the amount collected by the vehicle reaches its maximum capacity in a collection point, former arc is removed and vehicle capacity is renewed and zeroed again. The purpose of this phase is to predict the number of freights necessary for a circuit to be executed and identifying where it needs to be interrupted in order to restore capacity. If the circuit does not need to restore capacity, no arc is eliminated and the next step is skipped.

4. Arcs corresponding to the discharge freight trips are inserted in the circuit. Collection points where maximum capacity is reached is connected with treatment facility to unload, and connected back to the zeroed collection point to proceed the circuit execution. In the end, it also connects treatment facility to depot to complete the circuit. Like step 3, it is restricted to the waste flow being collected due to different waste treatment facilities being considered.

5. Finally, the best circuit will be selected between the two solutions being worked and a complete circuit considering depot and treatment facility trips, and capacity constraints with discharge freights will be returned.

Fusion Module

Two complete circuits with different waste flows are merged. Since the vehicles considered in this study are not multi-compartmented and do not carry separate materials, the mixed circuits will have to collect one waste flow in a row first, unload, and proceed with the next waste flow. As a result, there are only two possibilities for merging circuits, collecting organics first and then undifferentiated, or vice versa. Both options are evaluated and ultimately best solution is returned. The module is described in three steps. Briefly:

1. First arc of one of the circuits is eliminated, as well as the last of the other circuit. That is, the link between depot and the first collection point, either undifferentiated or organic and the link between the last collection point and the other treatment plant are eliminated.

2. Last arc of the considered first circuit becomes a discharge freight as the vehicle does not return to the depot but instead continues the mixed circuit with the collection of the next waste flow. The arc connecting the treatment facility to the first collection point of the subsequent circuit is then added.

3. Returns best performing mixed circuit of both alternatives.

Evaluation Module

Reduces circuits to their mass center in order to behave like a depot and then evaluates their attractiveness to incorporate new collection points from pilot project. Three criterions are taken into consideration, (i) the distance to the mass center of pilot project, (ii) the available space in collection vehicle and (iii) the available time of the circuit. To each criterion is assigned a parameter that defines a weight evaluation. In order to evaluate space and time criterions, routes must be designed for the circuits under evaluation. Therefore, this module incorporates Construction and Metamorphosis modules. If more than one circuit is considered for evaluation, the module returns a sorted list of circuits according with alculated attractiveness.

Allocation Module

Selects the most attractive circuits from the list returned by the previous module and allocates pilot project collection points to the circuits under study until they are all allocated.

Unlike other modules, which are guided by sequential instructions, this module is structured in two nested loops.

The main loop consists in selecting the most attractive circuit according to aforementioned module result and then allocating the most heavy collection point from pilot project remaining collection points list. This criterion is designed to ensure that larger points are allocated first so that there is no inefficiency regarding wasted available circuit space.

The nested loop consists in selecting the closest collection points from the one chosen in the main loop and allocating them to the selected circuit. Note that, while the first selected point is the heaviest to avoid long-term space inefficiencies, following collection points are selected according to proximity criteria, to reduce distances traveled and thus time spent on future designed routes. Nested loop will stop when there is no available space left to the next collection point, meaning the circuit at hand reached its maximum capacity.

At this point, the algorithm will return to the main loop and selects the next circuit to fill with pilot project collection points according to attractiveness, as well as the first collection point to be allocated. The algorithm only stops when all collection points from pilot project have been allocated to the considered circuits regardless of exceeding load and time constraints, returning the same circuits that were considered reconfigured to accommodate all pilot project zone collection points.

Final Scenario Procedures

The modules described above were developed as building blocks to achieve final procedures capable of solving each particular scenario problem. Final procedures are illustrated in Figure 3.

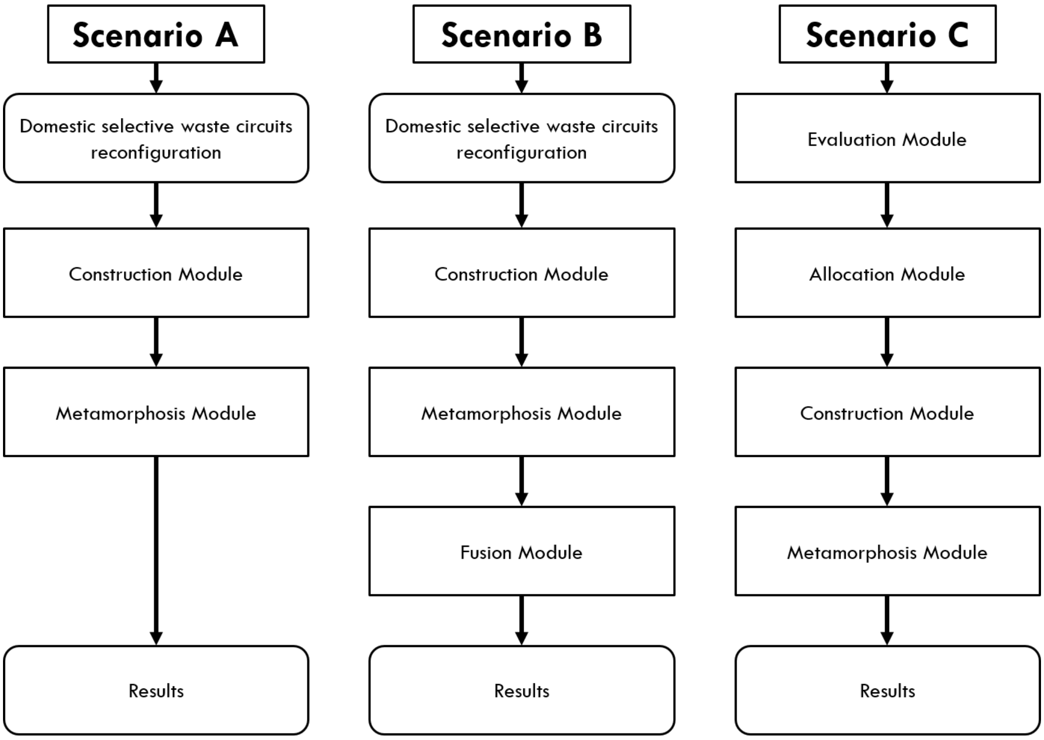

Figure 3 - Final procedures for each scenario

5. Results

The algorithm was developed and programmed in R version 3.6.1 (R Core Team, 2019) with extensive use of "TSP" library, developed by Michael Hahsler & Kurt Hornik (2019).

For each scenario, the procedures were applied resulting in a route for each circuit, with travelled distances and duration times. Since the objective of this paper is to summarise the results in order to compare scenarios it was necessary to calculate routes for all original circuits. These routes allow distances and times obtained to be summed up into a total scenario cost. The results are resumed in Table 1.

Table 1 - Total costs of scenarios

	Total Distance (m)	Total time (h)
Scenario A	944766	64,645
Scenario B	934082	64,632
Scenario C	995708	68,602

Scenario B was the one with shortest total distance and simultaneously shortest time spent were verified.

Scenario A has the advantage that in the long run it has a more intuitive distribution of collection points. However, its major disadvantage is the need for a circuit reconfiguration. This entails modifying collection schedules for the resident population. Although it seems like a minor consequence, this change can be strongly resisted by residents. Resistance that may jeopardize the correct removal of waste to be recycled on the presupposed days. Additionally, it will also be associated with communication costs to notify the population of changes made.

As for Scenario B, we can see that at the economic level it is the scenario that has the best performance at both the distance and the route length. In the joint metric of these two indicators, it may be considered the most favourable option. However, the fact that mixed circuits are made may incur some additional costs as freight is required to collect both materials. In the normal situation, contrary to what was assumed, daily productions are not constant, and may happen in other scenarios without having to carry out two freights. Additionally, it may cause some resistance from workers because they no longer have short routes to execute.

In Scenario C, existing resources are exploited as some of the organic circuits are not yet saturated. It would also be the easiest scenario to implement as only three circuits would be changed instead of four. However, it has been observed that this is the most costly scenario, and the fact that it has a longer total duration may cause some discomfort to workers.

6. Conclusions

This paper is motivated by the environmental risks caused by waste, the complexity of waste management and collection and the European campaign for the city of Lisbon.

We have presented the study of a complex vehicle routing problem with particular aspects to cope with real situations and applied to a Municipal Solid Waste Management System: integration of domestic organic waste collection in Lisbon, Portugal. This case study presents some new features regarding the classical VRP. The most important ones is the accommodation of restrictions related with different waste flows and a different way to deal with capacity constraints by introducing freights trips. Furthermore, a different approach is developed by partitioning the algorithm into several Modules to accommodate three distinct scenarios.

Results show that, when considering only additional costs to the system, this is, only economic factor, scenario B is the best to integrate domestic organic waste with MSWMS of Lisbon. However, at an organizational level this has some limitations and B can no longer the best choice. Those advantages and disadvantages are discussed. In addition, our results include the routing of vehicles, which can be used to optimise current system. Note that current MSWMS only have circuits, this is, a set of collection points aggregated, but none of them has executable routes associated with. Therefore, introducing routes could improve and optimise system total costs regardless of the problem treated in this study.

Regarding the integrated approach limitations, there is a lack of quantitative methods which would be necessary to priorize a further qualitative valuation and analysis of scenarios. Although the focus deviates from the development of numerical and exact methods, it is recognized that these, when properly incorporated, can add precision and objectivity to the study. Thus, the results should be considered as a tool that allows to acquire considerable knowledge about a given context and that stimulates both scenarios integration with the MSWMS. Furthermore, the limitations found in the Case Study include some factors such as data collection, resources available for the research and limited availability of corporate entities.

To conclude, this study presents a limited analysis of three options to integrate organic waste collection in Lisbon's MSWMS, tough it can be helpful with the initial decision making process and reducing system total costs with the construction of routes to current scenario.

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