Planning collection routes with multi-compartment vehicles

Adriano Dinis Oliveira[1], Tânia Rodrigues Pereira Ramos[1], Ana Lúcia Martins[1]

[1] Instituto Universitário de Lisboa (ISCTE-IUL), Business Research Unit (BRU), Portugal

Abstract This paper aims to assess the impact of using vehicles with multiple compartments in a recyclable waste collection system. Such systems perform single-material routes to collect three types of recyclable materials (paper, glass and plastic/metal), where vehicles with a single compartment are used. If vehicles with multi-compartments were used, two or even the three materials could be collected simultaneously without mixing them. A heuristic approach is developed to solve the multi-compartment vehicle routing problem and applied to a real waste collection system operating in Portugal.

1 Introduction

Material recycling, imposed by the European Union (EU), brought extra logistics challenges to the member states. Collection costs represent about 70% of the total costs for a recyclable waste collection system (Ramos et al. 2014). Given this figure, such systems are constantly studying different alternatives to increase efficiency and reduce cost. In this context, vehicle routing problems are of particular interest and several applications arise from the waste collection sector.

Regarding packaging waste, there are mainly two types of selective collection available in Portugal: drop-off containers or curbside (door-to-door). In the drop-off system, the citizens/consumers have to move to a container nearby their home to drop the separated materials; in the door-to-door system the recyclable containers are inside their home building and are collected at a predetermined day of the week. The main system used in Portugal is the drop-off containers. The three types of recyclable packaging materials (paper, glass and plastic/metal) are dropped by the consumers into special containers. Then, those materials are collected by the company responsible for the waste collection system of that area on a regular basis. The drop-off containers are mainly collected by a top loaded truck, with a single compartment. Therefore, single-material routes are performed, what implies that the same collection site is visited three different times to collect each material individually. One alternative to this kind of system is to use vehicles with compartments and collect two or even the three materials simultaneously without mixing them.

This study was motivated by a real recyclable waste collection system operating in Portugal that aims to assess the impact on the distance travelled by using vehicles with multiple compartments to collect the drop-off recyclable containers instead of using single compartments vehicles. For that, a heuristic approach is developed to solve the multi-compartment vehicle routing problem and applied to the real case study. The results regarding the distance travelled are compared with the current solution, where single-material routes are performed.

The paper is structured as follows: in section 2, a literature review on the Multi-Compartment Vehicle Routing Problem (MCVRP) is presented. The case study is described in section 3. In section 4 we propose a heuristic approach to solve the MCVRP. The results are presented and discussed in section 5. Lastly, in section 6 the conclusions are presented.

2 Literature Review

In the Capacitated Vehicle Routing Problem (CVRP) the customers request the delivery (or collection) of just one product. A homogenous vehicle fleet is based at a central depot and the optimal delivery or collection routes must be designed, respecting the capacity of the vehicles. In the Multi-Compartment Vehicle Routing Problem (MCVRP) the customers request the delivery (or collection) of different products which cannot be commingled during transport. For that, vehicles with multiple compartments are used to co-transport the products. In this case, the compartments capacity cannot be exceeded.

Despite several real life applications (namely in distribution of food and petrol), the MCVRP has not been studied extensively. However, some works have been recently published. El Fallahi et al. (2008) formulated the MCVRP and proposed three algorithms to solve it: a constructive heuristic, a memetic algorithm and a tabu search method. The authors adapted well-known instances for the classical VRP to test the methods proposed. Muyldermans and Pang (2010) presented a local search procedure for the MCVRP and have tested on CVRP instances and MCVRP instances. The authors also generated new instances to assess the benefits from using vehicles with multiple compartments on waste collection field. They compared the routing cost for co-collection (solving a MCVRP) with the routing cost for separate collection (solving a CVRP) and concluded that co-collection is better when the number of product to collected is higher, when the vehicle capacity increases, when the products are less bulky, when more clients request all commodities, when client density is lower and when the depot is more centrally located in the collection area. Derigs et al. (2011) developed and implemented a portfolio of different heuristic components for solving the MCVRP and tested on literature instances. Reed et al. (2014) proposed an ant colony algorithm and tested for the MCVRP with two compartments. Coelho and Laporte (2015) proposed a classification scheme for the fuel distribution problem regarding the ability to split the content of a compartment between several deliveries and the ability to split a customer tank to receive deliveries from different vehicles. The authors stated that only the unsplit-

unsplit problem is traditionally treated in the literature and the three other cases (split compartments-split tanks, split compartments-unsplit tanks, unsplit compartments-split tanks) are new and are modelled and solved for the first time in that work. A real-life application is presented by Lahyani et al. (2015). The authors tackled the olive oil collection problem in Tunisia, where three different grades must be kept separate during transportation. An exact branch-and-cut algorithm is proposed to solve the problem.

In face of this literature review, we can conclude that the MCVRP is getting more attention from the academia in the recent years but only literature instances have been tackled (with the exception of the work of Lahyani et al., 2015) . Real-life applications are seldom studied. Therefore, this work explores this opportunity and studies an application of the MCVRP in the collection of recyclable materials.

3 Case-study

In Portugal there are 30 recyclable waste collection systems. One of them is Valorsul, which is responsible for the selective collection in 14 municipalities located at West Region. Valorsul owns a vehicle fleet of 12 vehicles that is based at one depot located in the municipality of Cadaval. All vehicles have one compartment with 20 m^3, meaning that single-material routes are performed. Material glass is collected by a top loaded truck with no pressing function. Paper and plastic/metal are collected also by top loaded trucks, but with pressing function. The vehicle crew includes one driver and one assistant. There are 82 routes established: 26 for paper collection, 26 for plastic/metal collection and 30 for glass collection. Considering the collection routes performed between January and September 2013, Table 1 shows the average time between collections, number of containers collected by route, distance travelled per route and amount of material collected per route for each type of recyclable material.

Table 1 – Current indicators for Valorsul routes performed between January and September 2013 (average values)

Recyclable material	No. routes performed	Time between collections (days)	No. containers collected per route	Distance travelled per route (km)	Amount collected per route (ton)
Paper	816	9,3	82	135,3	2.8
Plastic/Metal	740	8,3	81	137,9	2.1
Glass	342	20,5	83	151,2	9.8

Paper and plastic/metal have similar indicators meaning that they could be collected together on the same route, if vehicles with two compartments were used. Glass differs greatly from the other materials regarding time interval between collections and the amount collected per route (given its high density compared with the other two materials). Therefore, the new approach that the company wants to test will consider the use of vehicles with two compartements to collect simultaneously paper and plastic/metal. These vehicles will have the same volume capacity than the ones actually used by the company (i.e. 20 m^3), that is going to be split accordingly to the density and weight produced of the two materials (see Section 5.1). It is considered that both compartments have pressing function. The aim of this work is to assess the benefits (in terms of distance to be travelled) of using multi-material routes instead of the traditional single-material routes (see Figure 1).

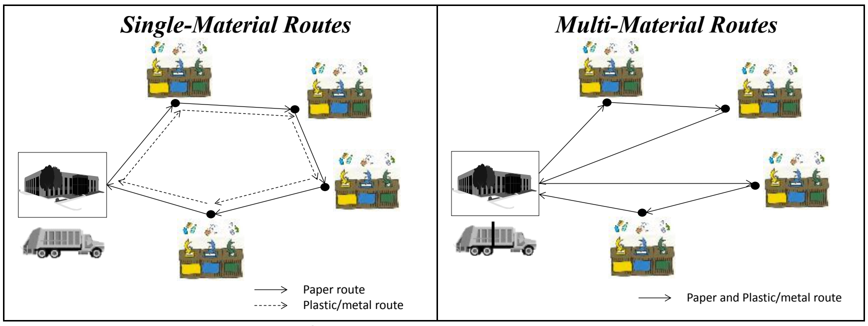

Figure 1 – Illustration of single-material routes *versus* multi-material routes

The two materials chosen to be collected together have different material density. At the containers, paper density is about 40 kg/m^3 and plastic/metal 20 kg/m^3; with vehicles with pressing function, densities increase to 250 kg/m^3 and 150 kg/m^3, respectively. These values were given by Valorsul. On the other hand, the annual amount collected of these two materials is also different. In 2012, Valorsul collected 15309 ton of paper and only 8583 ton of plastic/metal, meaning that the container's filling rate of each material is different. Given that the materials have different densities and different container's filling rates, there are two issues that must also be addressed when planning the collection routes with vehicles with multi-compartments: *(i)* how to define each compartment capacity and *(ii)* when to collect both containers.

4 Heuristic approach to solve the MCVRP

We propose a heuristic to solve the MCVRP based on the approach "cluster first-route second". When defining clusters, the container's filling rate, compartments capacity for each material, and the distance between the containers are taken into account. One of the main features of recyclable waste collection problems is that the containers have different filling rates among themselves due to its location. To tackle that, the main idea is to define large clusters with containers with low filling rates and small clusters with containers with high filling rates. Low filling rates mean that those containers have to be collected with a longer time interval between collections. Therefore, that cluster has to be visited fewer times during a year. On the other hand, clusters with containers with high filling rates have to be visited more frequently, thus, more times during a year. The idea is to have clusters with containers with similar collection frequencies since they are going to be collected in the same route.

The cluster phase starts by choosing a random site as a seed point and then more sites will be included to that cluster within a given radius of *R* km. For the sites included in that circle, the amounts to collect of the two materials in each site are summed and ranked in a descending order. Given this ranked list, the heuristic starts adding containers to the first cluster until no sites are available within the circle or one of the capacity of the vehicle compartments is exceeded. Then, another site is chosen as seed and the process is repeated until all sites are included in clusters. The radius value is a parameter and it is not known the best value to use. Therefore, several radius values will be tested. Moreover, as the seed points are randomly chosen, different solutions will be generated.

As a result of the clustering phase, we end up with *n* TSPs that need to be solved. We start by applying the savings algorithm (Clarke and Wright, 1964) followed by two local search procedures: two-point-move and 2-opt.

Given the interdependency between the filling rate of a container and the time interval between consecutive collections, it was considered an initial value for the time interval between collections in order to define the clusters and routes. After routes are defined, the time interval between collections (T) is maximized in order to decrease the number of times each route has to be performed in a year. To maximize that value it is taken into account the daily disposal rate of each container for each material (d_{im}), the vehicle compartments capacity for each material (V_m) and the containers capacity (C_m). For each route with *n* containers, the following problem is solved:

$$Max\ T \qquad (1)$$

$$\sum_{i=1}^{n} d_{im} T \leq V_m, \quad \forall m \qquad (2)$$

$$d_{im} T \leq C_{m,} \quad \forall i, \forall m \qquad (3)$$

$$T \text{ integer} \qquad (4)$$

The first phase of the heuristic (clusters definition) was coded in VBA. The second phase (route definition) was solved using the VRPH Library implemented in C++ available in the work of Groer (2008). The third phase (maximization problem) was solved using MS Excel Solver.

5 Application to the case-study

5.1 Data collection

Given the vast intervention area of Valorsul (more than 3000 km^2) and the high number of containers (7807 containers), it was decided to test the use of multi-compartments vehicles in a small area first (test-area). The test-area was defined taking into account the routes performed by the company. We select three routes for paper and three routes for plastic/metal considering that: *(i)* the routes should be close to each other to obtain a contiguous test-area, and *(ii)* the routes for each material should be as similar as possible, given the number of containers to collect and the time between collections, in order to be possible to implement a joint collection. The selected routes are characterized at Table 2.

Table 2 – Characteristics of the selected routes for the test-area

Selected Routes	Average distance (km)	No. of containers	Average time interval (days)	Average weight collected (kg)	Average daily amount collected by container (kg/container.day)
#4 Paper	106	107	6,02	4958	7,7
#4 Plastic/metal	106	108	5,98	2885	4,5
#7 Paper	87	92	7	5127	7,9
#7 Plastic/metal	86	87	5,56	2546	5,3
#13 Paper	130	90	7,6	4494	6,6
#13 Plastic/metal	128	90	7,03	2564	4,1

After selecting the test-area, we need to determine the amount to be collected in each collection site and the time between collections. For that, it was previously computed the average daily amount collected by container. This estimation was based on the time interval between two consecutive collections and on the average amount collected by container in each route. These results are shown also at Table 2. We consider the smallest time interval between two consecutive collections as the time interval to compute the amount to collect in each collection site. Therefore, we use the value of 5 days, but after the multi-material routes were defined, this value will be maximized for each route as explained at Section 4.

To decide the compartments capacity, we compute the ratio between the amount collected of paper and the amount collected of plastic/metal. We conclude that for each kg of paper collected, 0.62 kg of plastic/metal are collected. Given the density of both materials in the vehicles (250 kg/m^3 for paper and 150 kg/m^3 for plastic/metal) and the vehicle capacity (20 m^3), the vehicle should have 9.8 m^3 allocated to collect paper and 10,2m^3 to plastic/metal. This means that the compartments capacities are 2450 kg for paper and 1530 kg for plastic/metal.

5.2 Results

Given that the heuristic developed has a random element (the seed choice to create the clusters), we generate five solutions and present the average values obtained. Regarding the parameter radius, four different values were tested (20 km, 25 km, 30 km and 35 km).

Seven clusters/routes were defined to collect paper and plastic/metal containers within the test-area. Table 3 shows that the first clusters have more containers since the heuristic aggregate first the containers with lowest filling rates, thus more containers are visited in the first routes and less in the last routes.

At Figure 2 it is shown the usage rate of each compartment for each route of solution 5 with radius 20 km. It can be seen that until route 4 we have high usage rates for both compartments (higher than 64%) and for the last three routes we have some cases lower than 50% and a very lower rate for route 7.

Regarding distance, the best solutions found for each radius are presented at Table 4. However, at this point it is not possible to conclude what is the best solution considering annual distance because the time interval between collections has to be analyzed.

Table 3 – Average number of containers collected per cluster/route

Clusters/Routes	Radius 20 km	Radius 25 km	Radius 30 km	Radius 35 km
1	71,0	71,6	77,2	75,6
2	55,6	58,0	58,8	51,8
3	52,6	57,4	48,4	47,2
4	41,4	37,6	39,4	56,6
5	42,0	31,6	34.6	29,2
6	23,6	30,2	18,8	25,0
7	2,8	2,6	11,8	3,6

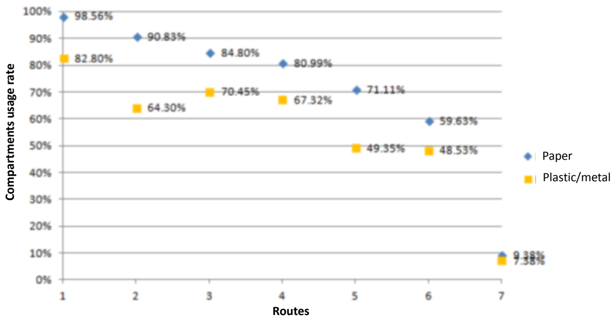

Figure 2 – Compartments usage rate for each route (radius=20km, solution 5)

Table 4 – Best solution for each radius value

	Radius 20 km	Radius 25 km	Radius 30 km	Radius 35 km
Best solution	Solution 5	Solution 2	Solution 5	Solution 1
Distance (km)	510,7	509,3	514,6	530,3

It was considered as an input data a time between collections of 5 days. However, this value could now be maximized given the compartments usage rates and the containers filling rates. If the compartments usage rate is less than 100% and all containers collected have a filling rate lower than 100%, that route could be performed with a 6 days interval, for example. Table 5 shows the time between collections maximized. For example, in the best solution with radius 20 km, two routes have increase the time between collection to 6 days and in one route that value increase to 7 days. This will have a great impact on the annual distance travelled. In fact, the best solution considering only the distance of each route (Table 4) is not the best solution considering the annual distance. At Table 5 it can be seen that the best solution is the one with radius of 20 km.

The current solution for the test-area implies six balanced routes in terms of number of containers collected, with a time between collection of 5.5 days to 7.6 days (see Table 2) and a total distance travelled per year of 35968 km. This means that performing multi-material routes decreases the total distance travelled in 5% (34273 km *vs.* 35968 km), but more routes are performed (7 routes *vs.* 6 routes) and they are more unbalanced regarding the number of containers to collected.

Table 5 – Time between collections for each route belonging to the best solution for each radius

	Radius 20 km	Radius 25 km	Radius 30 km	Radius 35 km
Best solution	Solution 5	Solution 2	Solution 5	Solution 1
Route 1	6	5	5	5
Route 2	5	5	5	7
Route 3	5	6	5	5
Route 4	5	7	5	5
Route 5	6	5	7	5
Route 6	7	5	5	5
Route 7	5	5	5	5
Annual Distance	**34273 km**	34946 km	36286 km	37248 km

6 Conclusions

This paper assesses the impact of using vehicles with two compartments to collect paper and plastic/metal simultaneously using real data from Valorsul. A heuristic is proposed to solve a multi-compartment vehicle routing problem and attention was given to the specific characteristics of a recyclable waste problem: different collection frequencies due to different filling rates among containers, materials with different densities at the containers and vehicles. The heuristic was applied to a test-area and savings of 5% were obtained when using vehicles with two compartments instead of one. However, the new routes proposed are unbalanced regarding the number of containers to collect, and this represent a drawback to the implementation of this solution. To overcome this drawback and as further work, the cluster phase should be improved in order to get all clusters with a greater and balanced number of containers to collect. Narrowing the radius value will contribute to solve this problem. This study should also be complemented with a feasibility study to assess the feasibility of the investment in new vehicles or in adapting the vehicles to have two compartments.

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