Restructuring service areas and vehicle routes in a recyclable waste collection system

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Abstract

The present work aims to develop a decision supporting tool to help the decision making process related to the planning of waste collection systems. Such systems involve more than one depot and the objective is to define the delimitation of service areas and the vehicles routes. The problem is modelled as a multi-product, multi-depot vehicle routing problem. A hybrid method that combines exact formulations with heuristic procedures is developed and applied to a real recyclable collection system whose managers want to restructure the current service areas as well as the vehicle routes used to collect three types of recyclable materials.

Keywords: Service Areas, Vehicle Routing, Multiple Depots

Introduction

In Europe, recycling, imposed by the European Union, has forced member states to develop new collection systems. The traditional routes defined for organic waste do not fit the particularities of recycling materials where different vehicles, collection rates, and bin locations are required. This situation motivated the creation of two different waste collection systems: selective and undifferentiated. The former is intended for recyclable products, while the latter is intended for the non-recyclable ones.

For recyclable products, the manufacturers are responsible to give an adequate destination to their products when they reach the end of their working life. However, that responsibility is often transferred to waste managing companies that need to create recyclable waste collection systems to deal with such products. The most common recyclable waste collection system is the one related to the packaging waste (paper, glass and plastic/metal). Such systems are responsible to collect, within a certain geographic area and on a regular basis, the three types of recyclable materials dropped into special containers by the final consumer. These materials are then sorted, at sorting stations, and delivered to recyclers.

The present work aims at developing a decision supporting tool to help the decision making process related to the planning and operation of waste collection systems. The developed model is applied to a real company responsible for a recyclable waste collection network covering 7 municipalities in southern Portugal. The company operates 5 depots (one of them also acts as a sorting station) and 1612 recyclable waste containers clustered in 230 collection sites, corresponding to localities or isolated locations. A collection site aggregates one or more containers of one or more recyclable materials. The existence of multiple depots requires, in this case, the definition of service areas by depot, establishing the responsibility of the different depots towards the collection sites. Therefore, each depot is responsible to collect a set of collection sites and to define the collection routes. The collection is currently performed by a fleet of 7 vehicles with no compartments, so each recyclable material has to be collected in separated routes. Two types of transportation flows need to be considered: inbound transportation, from the collection sites to the depots; and outbound transportation, from the depots to the sorting station. Therefore, besides considering the distance travelled to the collection sites, it is also necessary to account for the distance between depots and the sorting station.

The recyclable materials have different collection frequencies: glass has to be collect once a month; paper four times a month and plastic/metal twice a month. Since the lowest collection frequency is one month, a planning horizon of four weeks is considered.

The company in study used to define the service areas by depot considering the municipalities' boundaries. Moreover, all recyclable materials at each collection sites have to be collected from the same depot. Nowadays, the company desires to restructure the service areas in order to decrease the collection variable costs and wants to study the impact of having service areas defined by recyclable material (where the recyclable materials at each collection site could be collected from different depots) instead of having service areas defined by depot.

Based on the case in study the present work aims to support tactical decisions focusing on the delimitation of service areas in collection systems with more than one depot. Simultaneously, the associated vehicle routes are to be defined. The vehicle routes definition is here considered as a tactical decision since routes are to be maintained for a medium period of time (e.g. 1 to 6 months) due to the stability of the containers fulfilling rates. Thus we are dealing with static routes and not with dynamic ones. The routes defined are to be applied at the operational level, however they only need to be revised due to seasonal demands or due to a significant increase in the quantities dropped by the population into the containers. Since we want to establish the service areas and the vehicle routes, and we are dealing with three different products to be collected in separated routes, the problem is modelled as a multi-product, multi-depot vehicle routing problem. A hybrid method that combines exact and heuristic approaches is developed and applied to the case study.

Literature Review

The multi-depot vehicle routing problem (MDVRP) appears as a generalization of the vehicle routing problem (VRP) where apart from the definition of the vehicle routes, it is also necessary to decide from which depot customers are to be visited, since several depots are at stake. The MDVRP simultaneously establishes the service areas of each depot and the associated vehicle routes. The vehicle routes are defined such that: (1) each route starts and ends at the same depot, (2) each customer is visited exactly once by a vehicle, (3) the total demand of each route does not exceeds the vehicle capacity, (4) the total duration of each route (including travel and service times) does not exceeds a preset limit. The best solution is the one that minimizes the total routing cost.

Several models have been developed for the MDVRP, exploring both exact and approximate approaches. However, due to NP-hard combinatorial nature of the problem, the models proposed in the literature are mostly heuristics-based. Few exact algorithms are present in the literature. Laporte et al. (1984), as well as Laporte et al. (1988), developed exact branch and bound algorithms for solving the symmetric and asymmetric version of the MDVRP, respectively. Recently, Baldacci and Mingozzi (2009) developed an exact method for solving the Heterogeneous Vehicle Routing Problem (HVRP) that is capable to solve, among other problems, the MDVRP. On the other hand, when analysing heuristic algorithms to solve MDVRP, several ones have been proposed (Tillman and Cain (1972), Golden et al. (1977), Renaud et al. (1996), Salhi and Sari (1997), Lim and Wang (2005), Crevier et al. (2007), among others).

Focusing on the application of the vehicle routing problems to waste collection systems some works have been published. The first work was presented by Beltrami and Bodin (1974) where a heuristic algorithm for the Periodic Vehicle Routing Problem (PVRP) was developed and applied to the undifferentiated waste collection system of New York. Tung and Pinnoi (2000) developed a heuristic for the vehicle routing-scheduling problem and applied it to the waste collection system in Hanoi, Vietnam. Angelelli and Speranza (2002) developed a model based on a tabu search algorithm to solve a PVRP that fits different waste collection systems. Teixeira et al. (2004) presented a heuristic approach to solve a PVRP and applied it to a real case study involving the centre-littoral region of Portugal.

The applications to waste collection systems available in the literature are intrinsically related to the periodic issues of waste collection problems. However, to the best of our knowledge, the multiplicity of depots, the existence of transportation flows from the depots for the sorting station, and the multiplicity of products to be collected, aspects that frequently describe real collection systems, have never been studied. Therefore, the present work explores these opportunities and proposes a hybrid method that combines exact formulations with heuristic procedures to solve the multi-product, multi-depot vehicle routing problem with the objective of minimizing the total distance travelled (including inbound and outbound transportation).

Hybrid Method to Solve the Multi-Product, Multi-Depot VRP

Description

Figure 1 shows a schematic diagram of the proposed hybrid method. Since we are dealing with a multi-product problem, two alternative solutions could be produce regarding service areas: a) all recyclable materials at each collection site have to be collected from the same depot - each depot has only one service area common to all recyclable materials (service areas by depot); b) the recyclable materials at each collection site could be collected from different depots - each depot has M (M = number of recyclable materials) service areas (service area by recyclable material). Therefore, the hybrid method is prepared for these alternatives and involves three main steps that have a different sequential order as service areas are defined by depot or by recyclable material.

In both situations the first step of the hybrid method solves a single-product MDVRP where multi-depot routes are allowed. In the second step a heuristic procedure is applied to complete the service areas. Finally, in the third step a vehicle routing problem is solved for each depot and for each recyclable material. Steps 1 and 3 involve mathematical formulations that were developed accounting for the problem characteristics in study. Also the heuristic procedure explores the problem characteristics. A detailed description of the method is now performed.

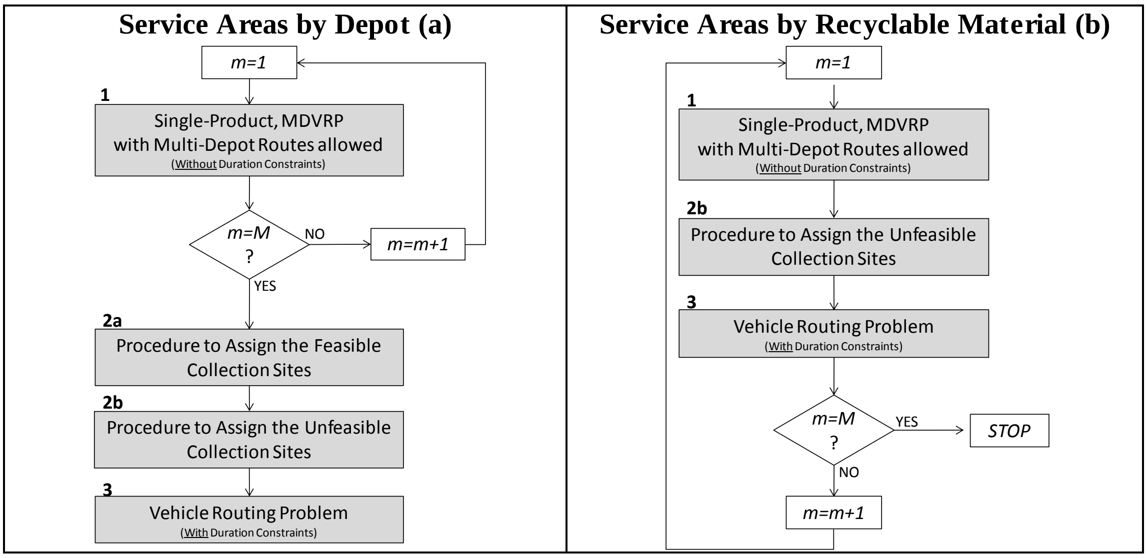

Figure 1- Structure of the proposed hybrid method – service areas by depot (a); service areas by material (b)

1) Single-Product, MDVRP with Multi-Depot Routes

The first step involves the relaxation of the Multi-Product, Multi-Depot VRP formulation into the Single-Product, Multi-Depot VRP with Multi-Depot Routes (from now designated as F1). From a problem where multiple products are considered and vehicle routes are restricted to start and finish at the same depot we consider a problem where just one product is considered and where multi-depot routes are allowed. In F1, the duration constraints are also relaxed. By solving F1, we obtain some collection sites that belong to feasible routes for the Single-Product, Multi-Depot VRP, meaning that they belong to a route that starts and finishes at the same depot; while some other collection sites belong to routes that start and finish at different depots, which for the original case are considered unfeasible.

The Multi-Depot VRP with Multi-Depot Routes was developed based on the two-commodity flow formulation for the CVRP, introduced by Baldacci et al. (2004). This formulation considers one real depot and one copy depot, and all vehicle fleet has to be used. In the proposed formulation instead of one real and one copy depot, we have a set of real depots and a set of copy depots, and we do not impose that all vehicles are to be used. The objective is to minimize the total distance travelled, including inbound and outbound transportation.

As input data, this step requires the distance between each node (collection sites, depots and sorting stations), the weight to be collected at each site (considering only one recyclable material) and the vehicle fleet capacity. The output will be a set of collection routes, where some routes start and end at the same depot (feasible routes) and some start and end at different depots (unfeasible routes). The collection sites that belong to feasible routes are assigned to the depot (not to a particular route or vehicle); collection sites that belong to unfeasible routes remain unassigned.

2) Heuristic Procedures

If service areas by depot are required (Figure 1a), it is necessary to analyze the results provided by the first module considering simultaneously all recyclable materials. Therefore, the hybrid method can only pursue to step 2 when step 1 is performed for all recyclable materials. In step 2a, the collection sites that belong to feasible routes for the same depot for all *M* or *M-1* materials are assigned to that depot. For instance, if collection site *i* is collected by a feasible route from depot d_1 for material m_1 and m_3, and by an unfeasible route for material m_2, site *i* is assigned to depot d_1. If however for material m_3, site *i* belongs to a feasible route from depot d_2, then site *i* will not be assigned to any depot at step 2a, since there is no agreement between the materials regarding their assignment. If service areas are defined by recyclable materials, step just described (2a in Figure 1a) is not executed since it is the scenario where materials do not have to be collected by the same depot.

For collection sites that remain unassigned, a heuristic procedure is run at step 2b allocating them to depots so as to complete the service areas by depot. This assignment is done through a greedy heuristic rule where the collection site is allocated to the nearest service area. Note that the previous assignments (at step 1 or step 2a) produced service areas to each depot, although uncompleted. Therefore, the free collection sites will be assigned to the nearest uncompleted service area. This is done by an iterative process where, node by node, the available collection site with the shortest distance to a service area is the first to be assigned. After this procedure, the service areas are updated and a new iteration is run until the complete set of unassigned nodes is empty. The distance considered includes the distance to the nearest service area (either a collection site already assigned or a depot) and a percentage of the distance between the depot and the sorting station. This percentage represents the vehicle occupancy rate based on the collected quantity of each recyclable material.

The output of step 2 is the service areas complete for each depot.

3) Vehicle Routing Problem

After phase two, service areas for each depot are already defined. It is now necessary to solve a vehicle routing problem for each depot and for each recyclable material to accomplish the multi-depot vehicle routing problem. The mathematical formulation used to solve the VRP is based on the two-commodity flow formulation (Baldacci et al., 2004), taking into account the route duration limit and the collection frequencies of the recyclable materials. To avoid the redefinition of the decisions variables with a third index representing the vehicle routes (x_{ijk} and y_{ijk}), it was developed a new mathematical formulation where two decision variables were added to carry out the duration constraints. These variables are TE_{ij} , which represents the exit time from site *i* to site *j* and TA_{ij} , which represents the arrival time to site *j* from site *i*. Some preliminary tests were run, and this formulation outperformed the one with three index decisions variables.

The first and third modules of the hybrid method are solved using the branch-and-bound algorithm implemented in the solver of the CPLEX Optimizer 12.1.0. The branch-and-bound computation time is arbitrarily limited to 1 hour, having in mind the tactical level of the problem to solve. The second module, with the heuristic procedures, is developed in MATLAB. An Intel(R) Core (TM) i7 CPU 930 @ 2.80 GHz is used.

Case-Study – A real recyclable waste collection system

The hybrid method presented above is now applied to the real case study describe in the introduction. The aim is to restructure the current service areas (see Figure 2) as well as the associated vehicle routes so as to reduce the variable costs of the existing collection system. A planning horizon of 20 working days is considered. The company's average distance travelled per month is about 30.000 Km and has an estimate cost per kilometre (including fuel consumption, driver costs, vehicle depreciation, insurance and maintenance of the vehicle) of 0,70€. The variable cost associated with the collection is then about 21.000€ per month and 252.000€ per year.

To reduce this cost, two scenarios are studied regarding service areas configuration: (1) service areas by depot and (2) service areas by recyclable material.

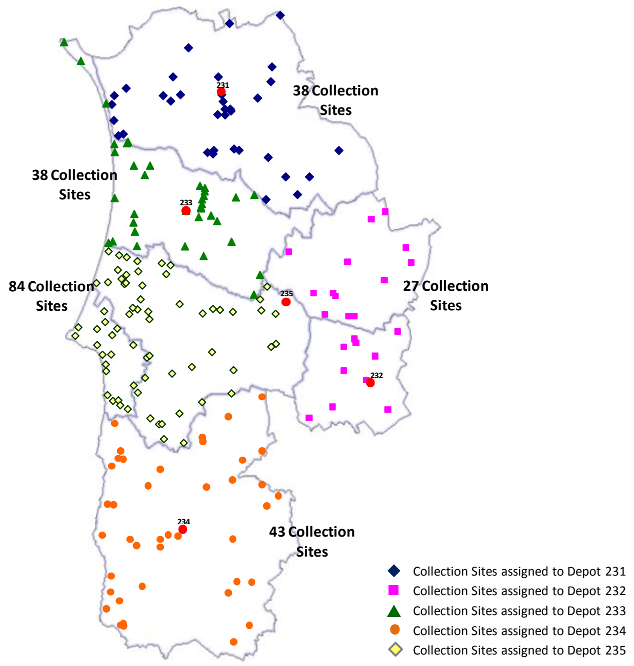

Figure 2 - Current Service Areas

Scenario 1 - Service areas by depot

For this scenario, and accordingly to the hybrid method (Figure 1a), the first module is run executed three times, one for each recyclable material. As a result, 104 collection sites are allocated to feasible routes for Glass, 129 collection sites to feasible routes for Paper and 114 collection sites to feasible routes for Plastic/Metal (see Table 1).

Table 1 - Results from the first module for each recyclable material

No Collection Sites	Glass	Paper	Plastic/Metal
Assigned to feasible routes	104	129	114
from Depot 231	2	14	6
from Depot 232	2	0	10
from Depot 233	25	27	24
from Depot 234	30	0	32
from Depot 235	45	88	42
Not assigned (unfeasible routes)	116	51	68
Without Recyclable Material*	10	50	48
Total	*230*	*230*	*230*

* Some collection sites do not have all the three recyclable materials to be collected

The computational statistics and objective function of such results are shown in Table 2. The first module deals with a problem dimension of 240 nodes, despite that, solutions with 8 and 10% of GAP are obtained within one hour.

Table 2 - Computational results for the first module for each product

	Glass	Paper	Plastic/Metal
Opt.Value (Km)	2917	10392	7572
CPU Time (secs)	3600	3600	3600
GAP (%)	10	10	8

At step 2a, analysing simultaneously the results from the first step for each recyclable material, 126 collection sites out of 230 are now assigned to depots. At step 2b, the remaining collection sites (104 sites) are iteratively assigned to the nearest uncompleted service area. The service areas obtained from step 2a and 2b are represented in Figure 3.

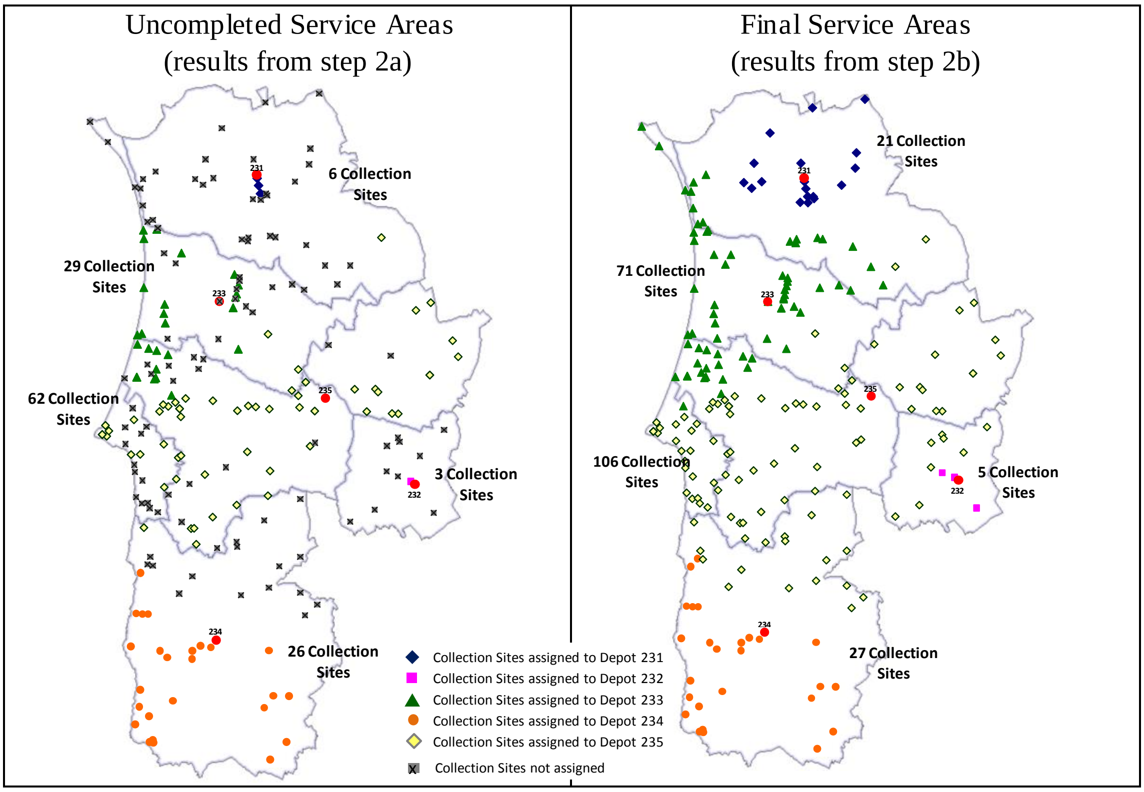

Figure 3 - Service areas in scenario 1

It can be seen that depot 235 has the largest service area (106 collection sites out of 230). This is easily explained by the fact that this depot is also the sorting station. Therefore, the model, in order to minimize the total distance travelled, assigns more collection sites to this depot avoiding the outbound transportation.

In step 3 the results show that for each depot and for each recyclable material, the total distance travelled with the proposed service areas is 24.060 Kms (see Figure 4). Therefore and as a conclusion it can be state that restructuring service areas and vehicles routes lead to a decrease on the total distance travelled in 20% when compared with the current solution. This represents an annual savings of 50.000€.

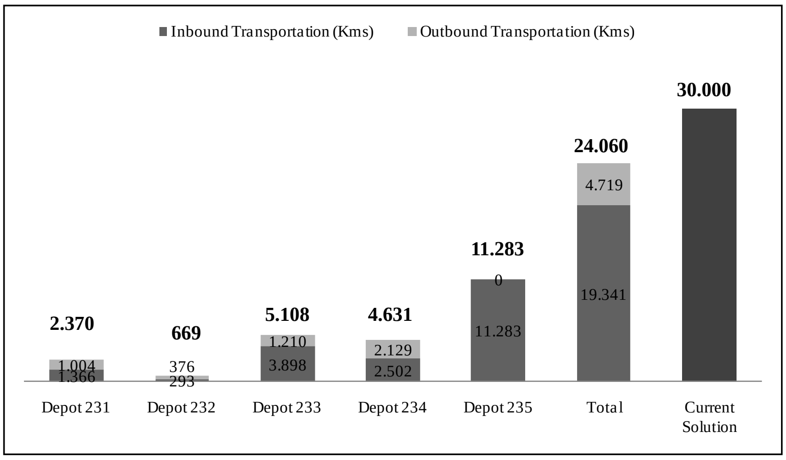

Figure 4 - Distance travelled for each depot in scenario 1

The computational results for the third module are shown in Table 3. This module proves the optimal solution in 8 (out of 15) instances and for the remaining, the GAP is acceptable for a real problem, never overcoming 6,8%.

Table 3 - Computational results for the third module

	Glass			Paper			Plastic		
Depots	**Opt.Value (Km)**	**CPU Time (sec)**	**GAP (%)**	**Opt.Value (Km)**	**CPU Time (sec)**	**GAP (%)**	**Opt.Value (Km)**	**CPU Time (sec)**	**GAP (%)**
Depot 231	295	5	0,0	1422	2	0,0	653	4	0,0
Depot 232	73	0,4	0,0	414	0,4	0,0	182	0,5	0,0
Depot 233	849	3600	6,0	2624	3600	3,7	1635	3600	6,3
Depot 234	576	403	0,0	2539	515	0,0	1516	3600	0,6
Depot 235	1675	3600	3,8	5280	3600	6,8	4328	3600	3,4

Scenario 2 - Service areas by recyclable material

In this scenario (Figure 1b) and according to the three recyclable materials, three different service areas will be generated. The hybrid method is fully executed three times, one for each recyclable material. The obtained service areas are substantially different from each other (see Figure 5). For instance, depot 235 collects 75% of the total of collection sites for paper while it collects only 37% and 42% for plastic/metal and glass, respectively. Paper is the material with a higher collection frequency meaning that the total quantity of paper collected over the timeframe is much higher than the other two materials. Therefore, this solution assigns more collection sites with paper to the depot that is simultaneously the sorting station, reducing the outbound transportation.

The total distance travelled in this scenario is 23.394 Km (see Figure 6). Defining service areas by recyclable material increases the inbound transportation in 6%, but decreases the outbound transportation in 41% when comparing to scenario 1, where service areas are defined by depot. The total distance travelled decreases 3% and 22% when comparing, respectively, with scenario 1 and with the current situation. This represents an annual savings of 55.000€ towards the current solution.

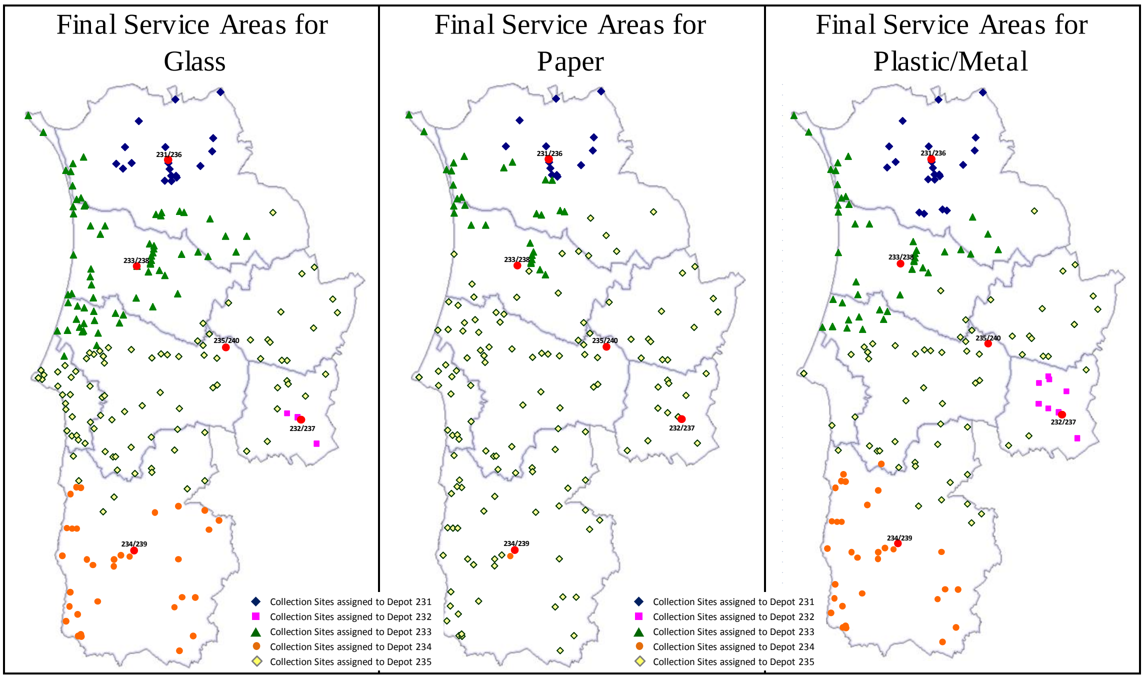

Figure 5 - Service areas by recyclable material

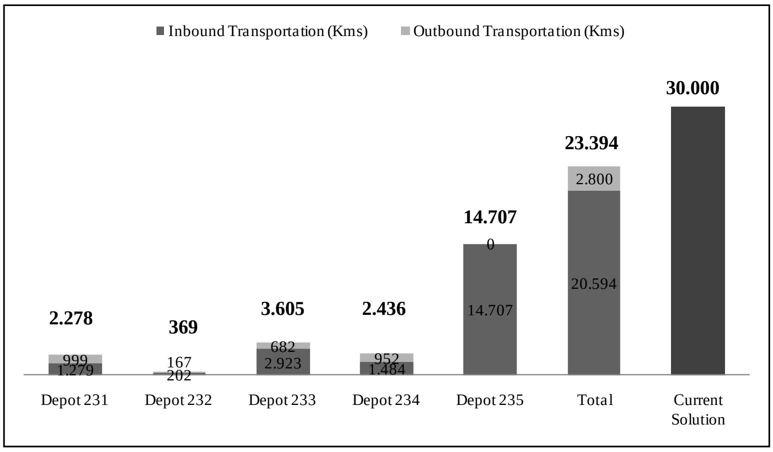

Figure 6 - Distance travelled for each depot in scenario 2

The computational results for third module are shown in Table 4. Optimality is proved in 7 instances and for the remaining 8 instances the GAP never overcomes 7%.

Table 4 - Computational results for the third module in scenario 2

Depots	Glass			Paper			Plastic		
	Opt.Value (Km)	CPU Time (sec)	GAP (%)	Opt.Value (Km)	CPU Time (sec)	GAP (%)	Opt.Value (Km)	CPU Time (sec)	GAP (%)
Depot 231	295	5	0,0	1251	10	0,0	732	30	0,0
Depot 232	73	0,4	0,0	-	-	-	296	5,0	0,0
Depot 233	886	3600	5,8	1142	3600	4,5	1577	3600	5,9
Depot 234	642	109	0,0	43	1	0,0	1751	3600	0,4
Depot 235	1580	3600	5,0	9209	3600	7,0	3918	3600	4,1

Conclusions

The present work addresses the solution of a multi-product, multi-depot vehicle routing problem often characteristic of real recyclable waste collection systems. A hybrid method is developed, which defines service areas and vehicle routes. The method combines two exact formulations with heuristic procedures.

The hybrid method is applied to a real case study that involves a recyclable collection system whose managers want to restructure the current service areas as well as vehicle routes. Two scenarios are studied in order to handle different alternatives proposed by the operations manager: scenario 1 - where service areas and vehicle routes are restructured assuming that the three recyclable materials at each collection site have to be collected from the same depot; scenario 2 – where service areas and vehicle routes are restructured assuming now that service areas are defined by recyclable material. The two scenarios studied are able to reduce the total distance travelled (including the inbound and outbound transportation) in 20% (scenario 1) and 22% (scenario 2) when compared to the current solution. Consequently, scenario 1 provides annual savings of 50.000€ and scenario 2 provides annual savings of 55.000€, regarding the variable cost associated to the collection and outbound transportation.

As main conclusion it can be stated that an efficient method was developed to support the decision maker when planning real recyclable collection systems. This allows the definition of service areas when dealing with multi-depots and more than one product. It also allows for the establishment of the associated routes. As future work, it will be important to consider the balancing of the working hours among depots. Furthermore, the periodic schedule of vehicle routes accordingly with the collection frequency will also be considered.

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