Minimizing CO_2 Emissions in a Recyclable Waste Collection System with Multiple Depots

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Abstract

The main activity in most logistics systems is transportation, which can be quite harmful to the environment. To mitigate these negative impacts, companies are looking for business practices that excel both economic and environmental goals. In this work, an environmental objective is included in the decision making process when planning waste collection systems. The main goal is to define service areas and routes that minimize CO_2 emissions of a system with multiple products and depots. A decomposition solution method is developed and applied to a real case-study in order to restructure the current operation and achieve a more environmental-friendly solution.

Keywords: Greenhouse Gas Emissions, Service Areas, Multi-Depot Vehicle Routing Problem

Introduction

A recyclable packaging waste collection system collects, within a certain geographic area and on a regular basis, the three types of recyclable materials (glass, paper and plastic/metal) dropped by the final consumer into special containers. These materials are then sorted, at sorting stations, and delivered to recyclers. Under this context, transportation and sorting are the main activities of such systems.

Although recycling contributes positively to the environment, the activity of collecting the recyclable waste is mainly a transportation activity that implies Greenhouse Gas emissions (GHG, as CO_2, CO, HC, NOx), resource consumption, noise, amongst other negative impacts to the environment. Being GHG emissions quite harmful, in particularly the CO_2 emissions, companies are seeking for transportation solutions that minimize CO_2 emissions, without disregarding economic goals.

The present work addresses such concern, and proposes a model that serves as the basis for a decision supporting tool that can help the decision making process related to the planning and operation of waste collection systems. The developed model is applied to a real case-study of a company responsible for a recyclable waste collection system covering 19 municipalities in Portugal. The company operates 2 depots (one of them also performs sorting operations) and 189 collection sites, corresponding to localities or isolated locations. A collection site aggregates one or more containers of one or more recyclable materials. The three recyclable materials have different collection frequencies: glass has to be collected one time every six weeks, paper one time every two weeks and plastic every three weeks. Therefore, a six-week planning horizon is considered. The existence of multiple depots requires, in this case, service areas definition by depot, where the responsibility of the different depots towards the collection sites is established. Therefore, each depot is responsible to collect a set of collection sites and to define the collection routes. Each recyclable material has to be collected in separated routes since the vehicle fleet has no compartments. Two types of transportation flows are considered: the inbound transportation, from the collection sites to the depots; and the outbound transportation, from the depots to the sorting station.

The service areas and the vehicle routes are currently defined by the company through the municipalities' boundaries. However, having nowadays new goals, the company wants to evaluate two main objectives: (i) assess the CO_2 emissions of the current solution and (ii) restructure the current operation so as to achieve a more environmental-friendly solution by (a) optimizing the vehicle routes while maintaining the current service areas or (b) restructuring both service areas and vehicle routes.

The problem in analysis is modeled as a multi-product, multi-depot vehicle routing problem (MP-MDVRP), since the definition of service areas and vehicle routes for three different products is envisaged. These routes are to be defined so that: (1) each route starts and ends at the same depot, (2) the total quantity collected in each route does not exceed the vehicle capacity, and (3) the total duration of each route (including travel and service times) does not exceeds a preset limit. The objective function considers the minimization of the total emissions of CO_2 (emitted by the inbound and outbound transportation). A decomposition solution method that breaks down the MP-MDVRP into four modules of exact formulations based on the two-commodity flow formulation (Baldacci et al. (2004)) is developed and applied to the case study.

Literature Review

The multi-depot vehicle routing problem appears as a generalization of the well known vehicle routing problem (VRP) where together with the definition of vehicle routes, it is also necessary to decide from which depot customers are to be visited, since several depots are at stake.

Several models have been developed for the MDVRP, exploring both exact and approximate approaches. However, due to the NP-hard combinatorial nature of the problem, the models proposed in the literature are mostly heuristics-based. Few exact algorithms have been 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, several heuristic algorithms have been developed to solve MDVRP (see Golden et al.(1977), Renaud et al. (1996), Salhi and Sari (1997), Lim and Wang (2005), Crevier et al. (2007), among others). In all of these works, the objective function is defined as the minimization of the inbound distance travelled. Although, as mentioned in the introduction section, it is often the case that companies acting in the transportation sector are nowadays concerned with environmental impacts and thus such aspect should be explored within the models. As stated by Sbihi and Eglese (2007), most of the articles published in the VRP field explored economic objectives and there is not much literature linking VRP models to green logistics issues. Nonetheless, some works have appeared recently exploring these aspects. Bektas and Laporte (2011) presented the Pollution-Routing Problem where pollution is taken into account in the objective function of the VRP. Erdogan and Miller-Hooks (2012) introduce the so-called Green Vehicle Routing Problem (G-VRP) where routes are defined taking into account a limited vehicle driving range as well as limited refueling infrastructure, which are challenges that arise when an alternative fuel-powered vehicle fleet is operated. These works are, to the best of authors knowledge, the only works where environmental concerns are taken into account in the definition of vehicle routes. The present work intends to pursue this area, considering explicitly environmental concerns in the definition of the service areas along with the vehicle routes in a logistics system with multiple depots. Moreover, a wider approach is developed, where both inbound and outbound flows are regarded.

Decomposition Solution Method for the Multi-Product, Multi-Depot VRP

Figure 1 shows a schematic diagram of the proposed decomposition method for solving the multi-product, multi-depot vehicle routing problem. This is structured in four modules of exact mathematical formulations.

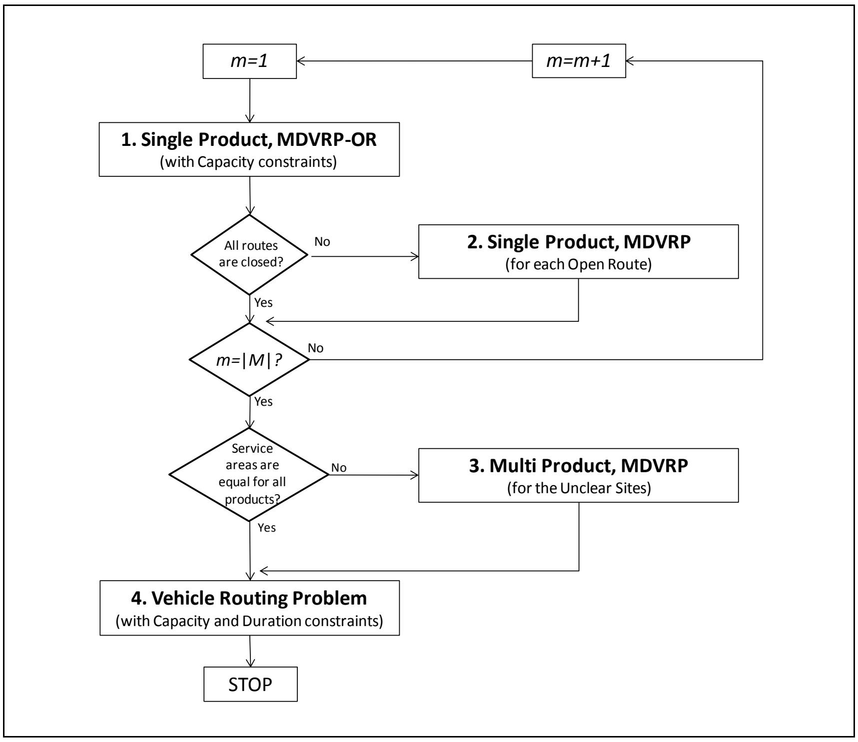

Figure 1- Structure of the decomposition method proposed to solve the MP-MDVRP

The first module involves the relaxation of the multi-product, multi-depot vehicle routing problem formulation (the original problem) into the single-product, multi-depot vehicle routing problem with open routes (MDVRP-OR). Instead of a problem where multiple products are considered simultaneously and the vehicle routes are restricted to start and finish at the same depot, we consider a problem where just one product is solved at a time and open routes between depots are allowed. By solving the first module, we could obtain routes that start and end at the same depot (closed routes) and routes that start and end at different depots (open routes). Since the original problem requires only closed routes, if open routes are obtained in the solution, the second module will be executed. In the second module, an exact formulation of the MDVRP is run considering only the collection sites that belong to the open routes. As a result, and for each open route, collection sites may be all assigned to a single depot or split among the several depots.

In the problem that we want to tackle, each site has multiple products to be collected in separated routes. When the problem is solved independently for each product that may lead to M (M = number of products) different service areas. After running modules 1 and 2 for all products, we can have situations where the same site is collected from different depots depending on the product. For instance and considering three products, a site i could be collected from depot d_1 for product m_1, but it could be collected from depot d_2 for product m_2, and from depot d_3 for product m_3. So, three cases may happen: *(i)* no agreement amongst the products regarding the sites assignment, *(ii)* agreement between two products or *(iii)* agreement among all products. The sites in cases *(i)* and *(ii)* are named as *unclear sites.* In module 3, an exact formulation for the multi-product, multi-depot vehicle routing problem is run for the unclear sites, where all products at each site are in routes that belong to the same depot. Therefore, each depot has the same service area for all products considered.

With the service areas defined for each depot, an exact formulation is now run at module 4 to solve a vehicle routing problem for each depot and each product defining the final collection routes. The four modules involve the development of generic mathematical formulations accounting for the problem characteristics in study. Those formulations are based on the two-commodity flow formulation for the CVRP, introduced by Baldacci et al. (2004).

The objective function considered in each module is the minimization of the total emissions of CO_2, emitted by the inbound and outbound transportation. Since the CO_2 emissions depend on the fuel consumption, the latter objective function takes into account the load of the vehicle in each arc traversed (curb weight plus load), the speed, the road angle, the engine features and frontal surface area of the vehicle (for both inbound and outbound vehicles), the coefficients of rolling resistance and drag, the air density and the gravitational constant (see Barth et al. (2004) and Bektas and Laporte (2011)). To convert fuel to CO_2 emissions we use the conversion factor of one liter of diesel fuel containing 2.6676 kg of CO_2 (Defra, 2011).

Equation (1) represents the fuel requirements F_{ij} (in litres) to traverse arc (i,j), where E_{ij} represents the energy requirements (in kJ), fd the fuel density (in g/l) and 43.2 kJ/g the lower heating value of a typical diesel fuel (Barth et al., 2004).

$$F_{ij} = E_{ij} / (43.2\, fd) \tag{1}$$

The energy requirements in given by the expression (2), where R is the engine friction factor (in kJ/rev/litre), representing the fuel energy used at zero power output to overcome engine friction per engine revolution and unit of engine displacement; N is the engine speed in revolutions per second (rev/s); B is the engine displacement in litres; d_{ij} is the distance between site i and j (in meters); v_{ij} is the speed on arc (i,j) in meters per second; P_{ij} is the total tractive power demand at the wheels to travel over arc (i,j) (in joules); ε is vehicle drivetrain efficiency and P_a is the engine power requirement for accessories, such as air conditioning (which from now on it will be considered null, i.e., $P_a=0$) and η is engine efficiency.

$$E_{ij} = R\, N\, B(d_{ij} / v_{ij}) + \left(P_{ij} / \varepsilon + P_a\right) / \eta / 1000 \tag{2}$$

The total tractive power demand at the wheels to travel over arc *(i,j)* is given by equation (3), where u is the acceleration (in m/s^2), g is the gravitational constant (9.81 m/s^2), θ is the road grade angle in degrees (we are assuming in Equation (3) that all arcs have the same road angle), C_r is the coefficient of rolling resistance, cw is the curb weight and μ_{ij} is the load carried by the vehicle on arc *(i,j)*, C_d is the drag coefficient, O is the frontal surface area of the vehicle (in m^2) and ρ is the air density (in kg/m^3).

$$P_{ij} = (u + g\sin\theta + gC_r\cos\theta)(cw + \mu_{ij})d_{ij} + 0.5C_d O\rho v_{ij}^2 d_{ij} \qquad (3)$$

Three decisions variables could be considered in the objective function in order to minimize the CO$_2$ emissions: the load carried by the vehicle on arc *(i,j)* – a continuous variable μ_{ij}; the speed on arc *(i,j)* – a continuous variable v_{ij}; and if the arc *(i,j)* is in the solution – a binary variable x_{ij}. In our model, we consider a constant speed in every arcs, thus speed is a parameter and not a decision variable.

The four modules of the decomposition solution 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 8 hours, having in mind the tactical level of the problem to solve. An Intel Xeon CPU X5680 @ 3.33GHz is used.

Case-Study – A real recyclable waste collection system

The decomposition solution method presented above is now applied to the real case study describe in the introduction. The aim is to assess the CO$_2$ emissions of the current solution and propose two new solutions: the first one where the current service areas are maintained and only the vehicle routes are restructured and a second one where both service areas and vehicle routes are reconfigured.

Current Solution: CO$_2$ emissions assessment

To assess the CO$_2$ emissions of the current solution, we list all the current routes and apply Equation (1) to determine the fuel consumption of each route and then compute the CO$_2$ emissions through the conversion factor. In **Error! Reference source not found.** is an illustrative example of this procedure for one current route. The parameters considered are: u=0, g=9.81,θ = 0°, cw=8000, Cd=0.77, Cr=0.01, O=6.5, ρ=1.204, R=0.2, N=33.3(3), B=9, ε=0.4, η=0.45 and fd=850. We considered an average speed between localities of 60 km/hour and an average speed within localities of 15 km/hour. The distance travelled in each arc and the load and number of containers to collect at each locality are shown in **Error! Reference source not found.**.

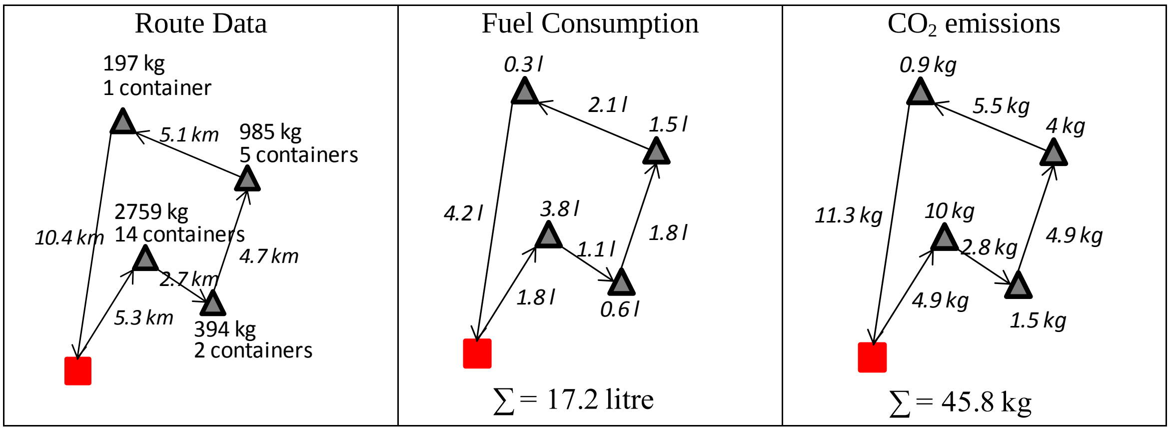

Figure 2 - Example of CO_2 emissions assessment in a route

Note that we have fuel consumption on arcs and on nodes, since nodes represent a collection site that aggregates one or more containers. Therefore, an average distance between containers of 500 metres is considered. For instance, in the first arc of the route, 1.8 litre of diesel are consumed since the vehicle travels 5.3 km, with no load, only its curb weight is considered:

$$P_{ij} = (0 + 9.81 \times 0 + 9.81 \times 0.01 \times 1)(8000 + 0) \times 5300 + 0.5 \times 0.77 \times 6.5 \times 1.204 \times 16.6^2 \times 5300$$
$$P_{ij} = 8\,559\,845\,J$$

$$E_{ij} = 0.2 \times 33.3 \times 9 \times (5300/16.6) + \left(P_{ij}/0.4 + 0\right)/0.45/1000$$
$$E_{ij} = 66\,692\,kJ$$

$$F_{ij} = E_{ij}/(43.2 \times 850)$$
$$F_{ij} = 1.8\,l$$

The route represented in **Error! Reference source not found.** consumes a total of 17.2 litre of fuel and emits 45.8 kg of CO_2.

Considering all current inbound and outbound routes, 35566 kg of CO_2 (see Figure 3) are emitted in a six-week period. Depot 190 is responsible for about 70% of the emissions, and since it is also the sorting station, no outbound emissions are present. For depot 191, about 56% of the total emissions are released by the outbound transportation. The total distance travelled in the current solution is 33377 km.

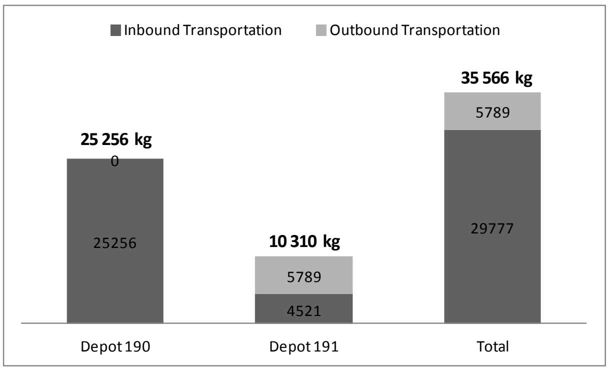

Figure 3 - CO_2 emissions by depot in the current solution

Proposed Solution I: Maintain service areas and restructure vehicle routes

The current service areas are shown in Figure ***4***. Depot 190 is responsible to collect 132 sites spread by 14 municipalities and depot 191 is responsible for 57 sites spread by five municipalities. The current service areas were defined accordingly with the municipalities boundaries. Since in this scenario service areas are to be maintained, only module 4 of the decomposition solution method will be executed in order to define vehicle routes that minimize CO_2 emissions.

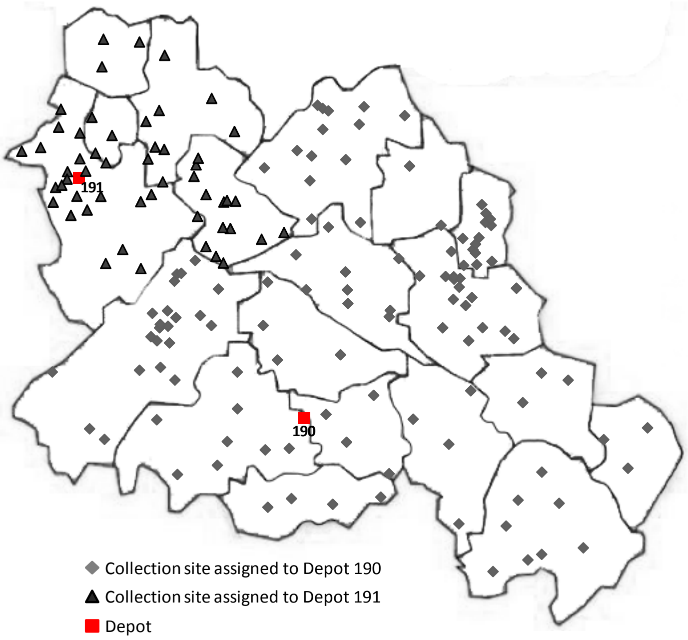

Figure 4 - Current Service Areas

In this scenario, 28443 kg of CO_2 (see Figure 5) are emitted, 20% less than with the current routes. The CO_2 emissions for depot 190 had decrease 24% and for depot 191 decrease 11%, where the outbound emissions remain the same since the service areas no dot suffer any change. The distance to be travelled also decrease in this scenario to 25761 km (less 23% than in the current solution).

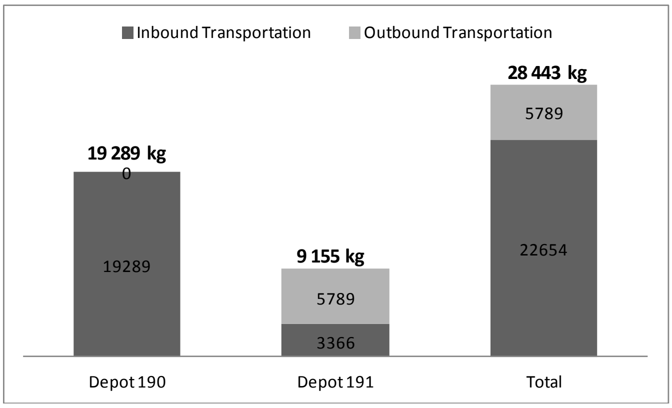

Figure 5 – CO_2 emissions by Depot in Scenario 1

The computational results for the forth module are shown in Table 1. In the first column we have the objective function value (OFV) in kg of CO_2, in the second column is the computational time in seconds and in third column there is the percentage of deviation between the OFV and the lower bound computed by CPLEX over the time limit. For the larger scale problems, the time limit was extended to 8 hours (28800 seconds).

Table 1 - Computational results for module 4 in scenario 1

	Glass			Paper			Plastic/Metal		
Depots	OFV	Time	GAP	OFV	Time	GAP	OFV	Time	GAP
Depot 190	3053	28800	9.4%	8645	28800	8.7%	7590	28800	4.2%
Depot 191	2161	3600	2.6%	3668	3600	1.7%	3325	3600	0.6%

Proposed Solution II: Restructure service areas and vehicle routes

In this scenario, the entire decomposition solution method will be applied in order to restructure both service areas and vehicle routes.

When applying module 1 to product "Glass", 28 closed routes were defined, with all collection sites assigned to depot 190. For product "Paper", 30 closed routes and 2 open routes were defined. Due to the open routes, module 2 was executed and the sites that belong to those were assigned to depot 190. Therefore, for product "Paper", 175 sites were assigned to depot 190 and only 3 sites to depot 191. For material "Plastic/Metal", 55 closed routes were defined, where 152 collection sites were assigned to depot 190 and 31 sites to depot 191. The service areas obtained at module 1 for each product are presented in **Error! Reference source not found.**. For product "Paper", the two open routes are identified.

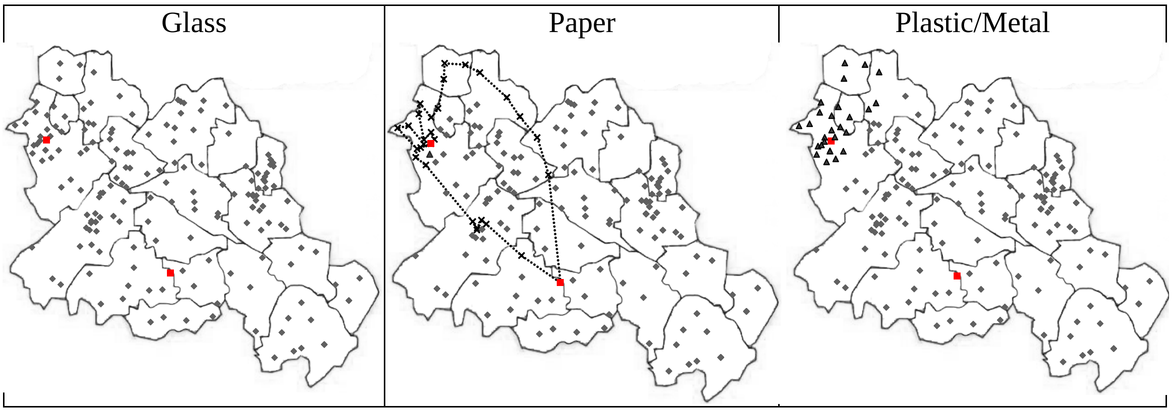

Figure 6 - Module 1 service areas by product

Since three different service areas were obtained, module 3 was executed for the unclear sites. The unclear sites are identified with a cross in Figure 7(a) and correspond to sites whose assignment do not match when the three service areas are overlapped.

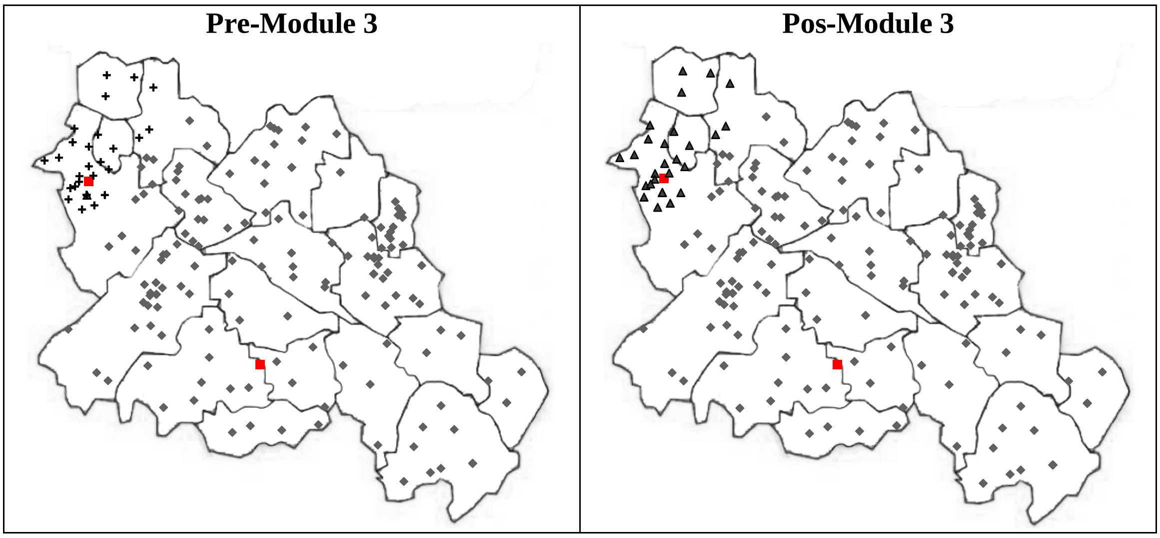

Figure 7 - Service areas (a) before and (b) after module 3 in scenario 2

There are 28 unclear sites that are the input for module 3. As a result, those sites are all assigned to depot 191. Therefore, depot 190 is responsible for 158 sites and depot 191 for 31 sites. Comparing with the current service areas, depot 190, which operates also as sorting station, is responsible to collect more sites, avoiding the outbound transportation, where the CO_2 emissions are higher. This because a longer distance is travelled, with a full loaded and larger vehicle in the outbound transportation than in inbound transportation.

In this scenario, 27484 kg of CO_2 are emitted, less 3.4% than in scenario 1 and less 23% than in the current solution. The inbound emissions increase 3% while the outbound emissions decrease 28%, comparing with scenario 1. The total distance travelled in this scenario is 25425 km.

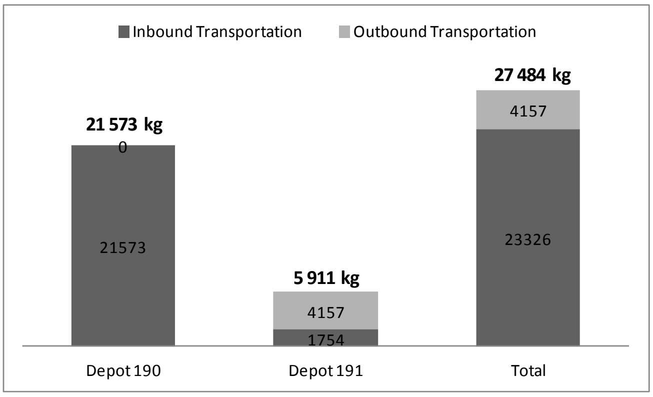

Figure 8 - CO_2 emissions by Depot in Scenario 2

The computational results for module 1 and 4 are shown in Table 2 and Table 3. For module 2, the two instances, corresponding to the two open routes obtained, were solved to optimality in few seconds. For module 3, the 28 unclear sites were split into three instances which were solved to optimality in less than one hour.

Table 2 - Computational results for module 1 in scenario 2

Products	**OFV**	**Time**	**GAP**
Glass	4255	28800	7.1%
Paper	11707	28800	5.4%
Plastic/Metal	10596	28800	3.3%

Table 3 - Computational results for module 4 in scenario 2

	Glass			**Paper**			**Plastic/Metal**		
Depots	OFV	Time	GAP	OFV	Time	GAP	OFV	Time	GAP
Depot 190	3585	28800	9.8%	9575	28800	9.7%	8413	28800	3.5%
Depot 191	1291	3600	0.6%	2445	97	0%	2173	36	0%

Comparing the CO_2 emissions of the current solution with the solutions proposed, a decrease of 23% is possible to reach if the company restructure both service areas and vehicle routes. If a more conservative approach is followed, i.e., keeping current service areas, a decrease of 20% is obtained. Furthermore, the total distance travelled is also improved in both outlined scenarios. A reduction of 23% and 24% is obtained with scenario 1 and 2, respectively.

Conclusions

In the present work, an environmental objective is included in the decision making process when planning waste collection systems. Such problem has not yet been addressed in the existing literature, to the authors best knowledge. The current work presents then an innovative approach where the main goal is to define service areas and vehicle routes that minimize the CO_2 emissions of a logistics system with multiple products and depots.

Furthermore, and knowing that the MP-MDVRP problems are very hard to be solved by exact models, this work also aims to contribute to overcome this drawback. This is achieved through the development of a decomposition method that breaks down the MP-MDVRP into four modules of exact formulations. The developed methodology is applied to a real recyclable waste collection system, where services areas and vehicle routes are restructured in order to minimize the CO_2 emissions of the current solution.

In the first scenario, where service areas are maintained, routes topology have to change since the minimization of CO_2 emissions seeks solutions where the vehicle travels less distance with heavy load. Therefore, the heaviest collection sites are left to be collected latter in the route. In the second scenario, where both operational variables can be modified, the current service areas also suffer changes, given that more collection sites are assigned to the depot that also operates as sorting station. When comparing both situations in terms of distance and environmental impacts it is concluded that the second scenario leads to a slightly better solution. When comparing the current solution with the studied scenarios significant gains are achieved.

As main conclusion, the present work identifies the need of restructuring both the current vehicle routes and the service areas leading to a better economical and environmental operation.

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