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RECYCLABLE PACKAGING WASTE COLLECTION SYSTEM: REDESIGNING SERVICE AREAS AND COLLECTION ROUTES IN A REAL CASE-STUDY

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ABSTRACT
This paper addresses the planning of a real recyclable packaging waste collection system operating in Portugal. The company's logistics network is characterized by the existence of multiple depots and multiple products to be collected in each site. Service areas and vehicle routes are currently defined respecting the municipal boundaries. A solution method based on mixed integer linear programming formulations is proposed to redesign service areas and collection routes under two scenarios: service areas by depot and by material. Also the scenario where the current service areas are maintained and only the collection routes are optimized is studied. Savings up to 20% in total distance are achieved by redesigning service areas and collection routes.

Keywords: Waste collection, Packaging waste, Service areas, Routing, Planning

INTRODUCTION
Waste production has increased significantly in recent years. According to INE [1], the production of waste in Portugal increased about 20% between 2004 and 2009, reaching the value of 5.185 million tons in 2009 (approximately 511 kg per capita). This growth enhances the need to manage waste effectively and encourages waste reduction, re-use and recycling. Recycling enables the recovery of raw materials, which otherwise would have a shorter life cycle. Therefore, it promotes the preservation of natural resources, energy saving and reduces the amount of landfilled waste.
Regarding packaging waste – glass, paper/cardboard and plastic/metal, the European Union imposed recycling targets to member states, forcing them to develop new collection systems suited to the specificities of this waste stream – the selective collection.
In Portugal there are 31 systems responsible to collect and sort packaging waste over the national territory. Valnor is one of those systems that is responsible for the collection and sorting of packaging waste produced in 19 municipalities in the North Alentejo region. The selective packaging waste collection involves 1275 glass bins, 1018 paper bins and 1017 plastic/metal bins, spread over 189 localities. The fleet includes 8 vehicles partitioned between two depots, one being the sorting station. The existence of multiple depots requires, in this case, service areas definition by depot, where the depot responsibility towards the collection sites is established. Each recyclable material has to be collected in separated routes since the vehicles have 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 company currently defines service areas and the vehicle routes through the municipalities' boundaries. Moreover, all recyclable materials in each collection site have to be collected from the same depot. Under this context, and having in mind that such assumptions may have some scope for improvement, the company desires to have analyzed the service areas and vehicle routes in order to decrease the collection variable costs.

Bearing in mind these companies objectives and knowing that depots service areas and collection routes for the three recyclable materials are to be defined with the objective of minimizing the total distance travelled (including inbound and outbound transportation), the problem is modeled as a multi-product, multi-depot vehicle routing problem. Due to the computational burden of such problem, a decomposition solution method based on mixed integer linear programming (MILP) formulations is developed and applied to the real case study.

LITERATURE REVIEW

Routing problems consist on the definition of optimal delivery or collection routes from a central depot to a set of geographically scattered customers, subject to various constraints. Such problems are common to a large range of logistics systems and have a significant economic impact on the planning and operation of these systems. The multi-depot vehicle routing problem (MDVRP) appears as a generalization of the vehicle routing problem (VRP) where beyond the definition of vehicle routes it is also necessary to decide from which depot the 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 typically the one that minimizes the total routing cost.

Several models have been developed for the MDVRP, exploring both exact and approximate solutions. Few exact algorithms have been present in the literature. Laporte et al.[2], Laporte et al.[3] and Baldacci and Mingozzi [4] developed exact method for solving the MDVRP. On the other hand, when analyzing approximated methods, several approaches have been proposed: *(i)* approaching the problem in two steps, where at the first step the customers are assigned to a depot accordingly with an assignment rule and at the second step, for each depot, it is solved a VRP [5]; *(ii)* approaching the problem in one step, where the assignment and routing are performed simultaneously [6]; *(iii)* building a initial solution and applying meta-heuristics [7].

There are some MDVRP variants studied in the literature. Crevier et al.[8] studied the MDVRP with Inter-Depot Routes, Vidal et al.[9] studied the Multi-Depot Periodic VRP, Bettinelli et al. [10] explored the Multi-Depot Heterogeneous VRP with Time Windows. Parthanadee and Logendran [11] studied a distribution problem with multiple depots, periodic and multiple products.

The application of routing problems to waste collection systems brings new characteristics which lead to different variants of routing problems. Tung and Pinnoi [12], Angelelli and Speranza [13] and Teixeira et al. [14] studied a waste collection problem where the collection sites have different collection frequencies – the Periodic Vehicle Routing Problem. When dealing with household waste, the problem is frequently modeled as a Capacitated Arc Routing Problem (CARP), where all arcs in a graph have to be visited, to allow waste collection in every street of a city (see [15]). For the commercial waste collection, the problem is frequently modeled as a VRP with Time-Windows since commercial customers often imposed time-windows to be respected (see [16]).

THE MULTI-PRODUCT MULTI-DEPOT VEHICLE ROUTING PROBLEM

Problem description

The MDVRP considers client’s demand of just one product. The MP-MDVRP considers that the demand of each client could involve a set of products M. Combining products multiplicity with depots multiplicity, two alternative solutions could be created regarding the service areas: a) all products at a site have to be collected by the same depot - each depot has only one service area which is common to all products (service areas by depot); b) the products at each site can be collected from different depots - each depot has $|M|$ service areas (service areas by material). In the first case, the problem is modeled as a multi-product, multi-depot vehicle routing problem (MP-MDVRP), which consists in defining the optimal routes of distribution (or collection) from multiple depots, imposing that all products on each client have to be visited by the same depot. This is the current practice in the company being studied. In the second case, the problem is modeled as a multi-depot vehicle routing problem (MDVRP) for each product, as the problem can be solved independently for each product. This is the alternative solution to the current company’s practice which is studied in this work.

Decomposition solution method

To solve the MP-MDVRP a decomposition solution method was developed. This method breaks down the MP-MDVRP into four modules and allows the study of different service areas configurations, as service areas by depot and by recyclable material. Fig. 1 shows a schematic diagram of the proposed method. If service areas by depot are required, a MP-MDVRP as to be solved, and the four modules are run. If service areas by recyclable material are required, a MDVRP for each material is run, and only modules 1, 2 and 4 are executed. Lastly, if service areas are previously defined, a VRP as to be solved, and only module 4 is run.

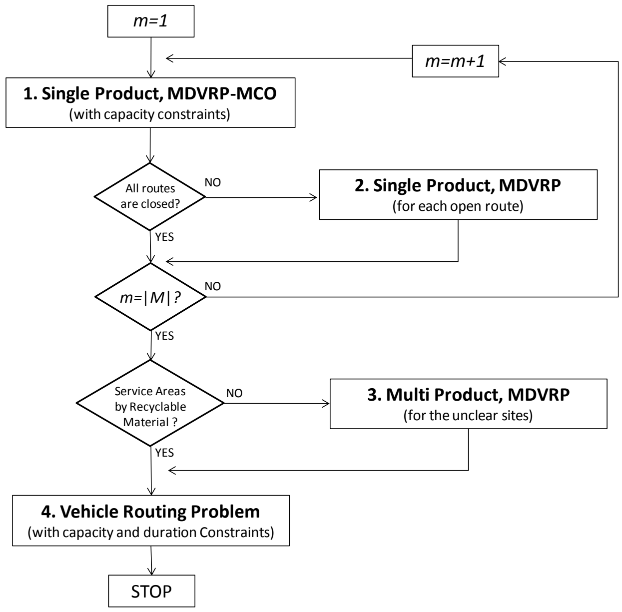

Fig. 1 Flowchart for the decomposition solution method

The first module involves the relaxation of the MP-MDVRP (the original problem) into a Single-Product, Multi-Depot Vehicle Routing Problem with Mixed Closed and Open Routes (MDVRP-MCO). A single product collection problem where open routes between depots are allowed is then considered. This module is run as many times as the number of different materials considered in the problem. In the solution of this first module, we can 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 defines only closed routes, if open routes are obtained, then the second module must be executed. The sites that belong to the open routes are the input data for the second module, where a formulation for the MDVRP is solved. Since in the MDVRP only closed routes are defined, after the execution of module 2, the sites that belonged to open routes are naturally assigned to the depots.

Furthermore, if service areas by recyclable material are required then, after obtaining only closed routes, module 4 is run. This involves the solution of a Vehicle Routing Problem with capacity and duration constraints for each depot and for each recyclable material. On the other hand, if service areas by depot are required, module 3 has to be run before module 4. Service areas by depot imply that all packaging materials at each collection site are collected from the same depot. Comparing the service areas defined for each material in the previous modules, some sites may not respect that rule. Such sites are called the “unclear sites” since there is no agreement among the packaging materials about their assignment to depots. For those sites a Multi-Product, MDVRP is solved. All modules involve the development of generic MILP formulations that were implemented in GAMS 23.7 and solved through the CPLEX Optimizer 12.3.0, on an Intel Xeon CPU X5680 @ 3.33GHz.

RESULTS

The recyclable waste collection system in study has 2 depots and 189 collections sites that correspond to localities or isolated places. The system is managed under a municipal perspective, where service areas and routes were defined respecting the municipal boundaries. In order to reduce the variable collection cost of the current solution, the solution approach developed is applied to the case study. To better support the decision-making process, three scenarios are studied regarding different service areas configuration: (1) maintaining the current service areas and optimize only collection routes; (2) redesigning service areas by recyclable material (each depot may have three different service areas), (3) redesigning service areas by depot (each depot has only a service area common to all three materials).

Scenario 1: Maintaining the current service areas

Fig. 2 shows the current service areas. Depot 1 is responsible to collect 57 sites while depot 2 is responsible for collecting 132 sites (depot 2 also operates as sorting station). Module 4 was run for each depot and each recyclable material and a solution with a total of 29.399 km per month was obtained, where 25.751 km (about 88%) corresponds to inbound transportation and 3.648 km (about 12%) to outbound transportation. As an illustrative example, Fig. 2 also shows the proposed paper routes from depot 1. It can be seen that eight routes were defined, where, on the contrary to the current plan, the routes do not confine to the municipal boundaries. For example, route #1 traverses five different municipalities.

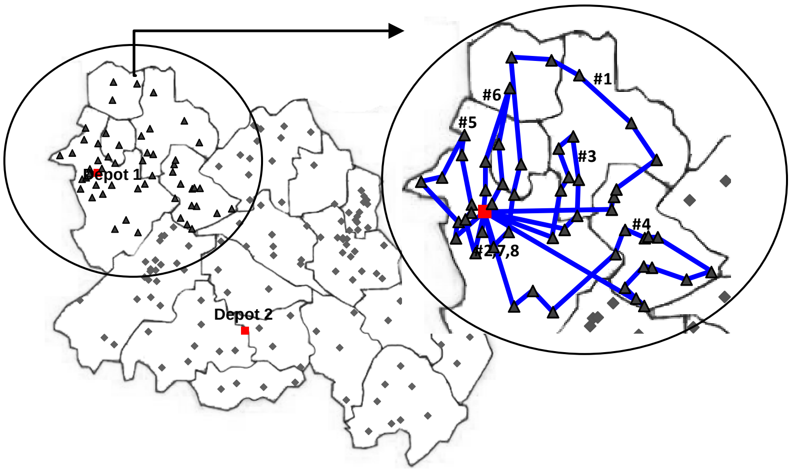

Fig. 2 Current service areas

Scenario 2: Redesigning service areas by recyclable material

To redesign the service areas by recyclable material, modules 1, 2 and 4 were run. Three different service areas were obtained, one for each recyclable material (see Fig. 3). Depot 1 is responsible to collect only seven sites with material Glass, while the same depot is responsible to collect 33 sites with Paper and 40 sites with Plastic/Metal. In this scenario, a total of 24 802 km have to be travelled. Comparing with scenario 1, depot 2 has an increase of 9% in total distance but depot 2 decreases the total distance in 58%. The overall distance decrease 16% comparing with scenario 1.

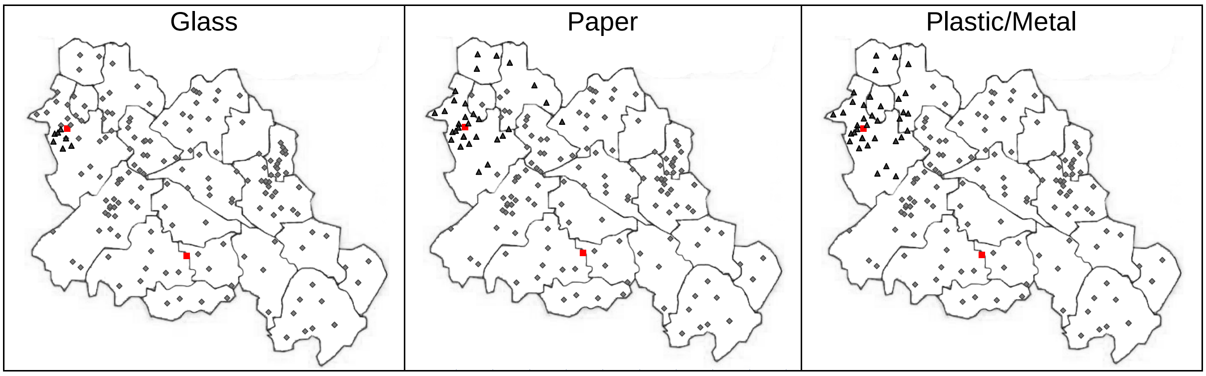

Fig. 3 Proposed service areas by recyclable material

Scenario 3: Redesigning service areas by depot

In this scenario one common service area is defined for the three materials. For that, all modules were run. Fig. 4 shows the proposed service areas by depot. This solution implies a total of 25 290 km to be travelled, meaning that redesigning the service areas by depot allows a reduction of 14% in the total distance comparing with the current ones (scenario 1).

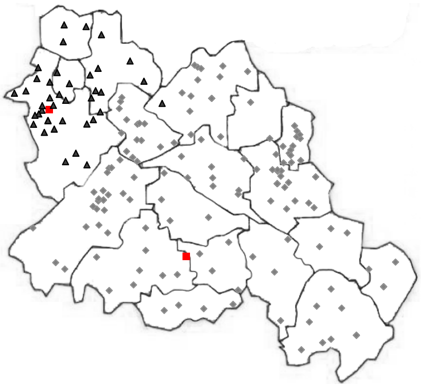

Fig. 4 Proposed service areas by depot

Computational Results

The computational results for module 1 are given at Table 1. Those results were used at scenario 2 and 3. Because this module deals with the largest instance (it considers the 189 sites simultaneously) and influences the results of the following modules, we consider a largest processing time (8 hours). The solutions obtained show low gaps (lower than 5%) considering the size of the instances run.

Table 1 Computational results for module 1

Recyclable Material	O.F.V (km)	Time (s)	Gap (%)
Paper	*10817*	*28800*	*4.9%*
Plastic/Metal	*10140*	*28800*	*3.3%*
Glass	*3600*	*28800*	*4.5%*

Regarding module 2, six runs were made as six open routes were obtained from module 1. The six instances were solved to optimality in less than one minute. Module 3 is run with the 32 unclear sites for scenario 3. It was solved to optimality in less than one hour. Module 4 is run in all scenarios. Their computational results are shown at Table 2. Five instances were solved to optimality, while seven show gaps inferior to 5%. For the largest instances, higher gaps were obtained. We limit the time to one hour (3600 s). If the gap obtained was higher than 5%, we run again for 4 hours extra in order to get better solutions.

Table 2 Computational results for module 4

		Depot 1			*Depot 2*		
		O.F.V (km)	*Time (s)*	*Gap (%)*	*O.F.V (km)*	*Time (s)*	*Gap (%)*
Scenario 1	*Paper*	*4328*	*18000*	*3.6%*	*8393*	*18000*	*4.3%*
	Plastic/Metal	*4421*	*3600*	*1.4%*	*7672*	*18000*	*3.7%*
	Glass	*1942*	*18000*	*6.1%*	*2643*	*18000*	*8.0%*
Scenario 2	*Paper*	*2070*	*22*	*0.0%*	*8968*	*18000*	*8.3%*
	Plastic/Metal	*2163*	*43*	*0.0%*	*7977*	*3600*	*3.7%*
	Glass	*259*	*1*	*0.0%*	*3366*	*18000*	*9.1%*
Scenario 3	*Paper*	*2422*	*565*	*0.0%*	*8693*	*18000*	*8.4%*
	Plastic/Metal	*2275*	*53*	*0.0%*	*7923*	*3600*	*3.7%*
	Glass	*1200*	*3600*	*1.8%*	*2779*	*18000*	*9.7%*

DISCUSSION

The proposed method was applied to the case study and it was able to find more advantageous solutions than the one currently implemented, where 31000 km are travelled per month.

Considering a more conservative scenario (scenario 1), where the current service areas are maintained, the company decreases 5% in the total distance traveled by just redesigning and optimizing the collection routes. This scenario only requires drivers training to implement new collection routes. Choosing an intermediate scenario, in which service areas are restructured, maintaining the collection of all materials from the same depot (scenario 3), it is possible to obtain a reduction of 18%. In this scenario, a greater number of collection sites are collected from depot 2 (146 against 132 in the current solution), which also operates as a sorting station. Scenario 3 involves a transference of collection sites that are currently under the responsibility of depot 1 to depot 2. The breakthrough scenario (scenario 2) modifies the current logic of all materials being collected from the same depot. In this case, each depot has to manage three different service areas according to each recyclable material. This scenario leads to a decrease of 20% in the current total distance travelled but it is the more complex to manage. Furthermore, this solution implies an integrated information system among the depots. Note that, currently, when a container is collected, information is recorded on the filling rate of the other containers (one collection point consists of three containers, one for each material.) In this scenario, the depot that collects one material at one collection point might not be the same that collects the other materials. Therefore, if no integrated information system exists, the information on the filling rates can be missed and that is essential information to re-plan the routes in case of over or under loading containers.

As main conclusion, the present work supports the need of redesigning the current company's service areas in order to reduce the variable costs associated with the collection of recyclable packaging materials. In an environment where companies struggler for reducing their costs and increase their efficiency, new solutions have to be pursuit, even though they break with current management policies institutionalized over the years.

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