Comparing urban solid waste collection routes obtained through the application of heuristics and GIS

Fábio Victorino

Department of Engineering and Management, Instituto Superior Técnico, Universidade de Lisboa

October, 2016

Abstract

Solid waste management is a complex process, being the collection and transportation of urban solid waste (USW) the most expensive of its operations. Amarsul is the company responsible for collecting recyclable USW in the district of Setúbal, in Portugal, including the recyclable glass waste in Barreiro municipality.

Amarsul's glass collection system includes 230 containers, distributed in five different circuits, and two different types of collection vehicles. Being a complex system it is important to determine efficient collection routes that serve all the containers in each circuit, while minimizing separately the distance travelled and the time spent by both vehicles.

The scope of this paper is then to present and compare two different approaches for solving Amarsul's Vehicle Routing Problem (VRP) – a Geographic Information System (GIS) and a Decision Support System (DSS) – taking into consideration a pre-defined set of constraints (*e.g.* service times, maximum work shift times, etc.). The GIS used was ArcGIS, namely the Network Analyst extension which applies a tabu search metaheuristic. The DSS routePlanner was developed specially for this case and implemented the Clarke and Wright savings algorithm (1962) and the 2-Opt improvement heuristic (Flood, 1956). Both approaches were compared based on a set of indicators, also developed for this study.

Keywords: urban solid waste management, vehicle routing problem, geographic information system, decision support system, Clarke and Wright savings algorithm, 2-Opt improvement heuristic.

1. Introduction

Solid Waste Management is a complex multifunctional process that comprehends activities such as waste generation, handling and storage, collection and transportation, as well as processing and disposal (Tchobanoglous, 2003).

The urban solid waste (USW) management sector in Mainland Portugal was structured and monitored based on the "*Plano Estratégico para os Resíduos Sólidos Urbanos"* (PERSU) (MA, 1997), which was reviewed later on to include international guidelines. From this revision was created the PERSU II, which defined USW policies adjusted to the country's commitments for pollutant gas emissions' reduction assumed in the Quioto Protocol (MAOTDR, 2007).

The collection and transportation is the most expensive waste management operation (Tchobanoglous, 2003). The vehicles used during this operation are often idling without moving, which represents an inefficient usage of fuel and high pollutant gas emissions. For this fact, Gaines *et al.* (2006) classified the waste collection vehicles between the five worst types of truck in terms of fuel usage efficiency.

The high amount of fuel consumed by waste collection vehicles contributes to Portugal's energy dependence (Amador, 2010). Also, the high cost of transporting USW overloads the total costs of waste management. Thus, making the USW collection and transportation more efficient has economic and environmental benefits. One of the ways to achieve it is by optimizing the routes travelled. Nguyen and Wilson (2010) estimated that using optimized routes could reduce about 7.5 l/day for each vehicle.

The scope of this study is then to obtain an efficient set of USW collection and transportation routes for a specific Portuguese case study – the Amarsul case – by applying adequate methods.

The remainder of this paper is organized as follows: section 2 characterizes the glass waste collection system of Amarsul; section 3 presents a brief overview of related literature; section 4 describes the used approaches for solving Amarsul's VRP; section 5 analyses the results obtained; and section 6 concludes the paper with some final remarks and a proposal of future work.

2. The Amarsul case study

Amarsul is the company that collects recyclable USW in the district of Setúbal, including the recyclable glass waste in Barreiro. Below is characterized its glass waste collection system:

- 230 selective collection containers and 1 waste treatment plant;
- 5 different collection circuits whose containers are to be collected in the same day, being:
  - 3 mainly urban with collection containers concentrated in heavily populated areas;
  - 2 mainly extra urban or rural with containers dispersed in areas with more population and areas with less population;
- 2 types of diesel collection vehicles that can be used: vehicle A with a maximum capacity of 11.5 m^3; and vehicle B with a maximum capacity of 15.2 m^3;
- 300 minutes of maximum vehicle operation time (maximum work shift);
- 4.5 minutes of average collection time in each container;
- 10 minutes of average vehicle unloading time at the waste treatment plant;
- 3 minutes of average waiting time in traffic.

3. Literature review

The efficient allocation of companies' resources is a highly important challenge. Logistics, for example, aims at maximizing its operations efficiency and minimizing its costs. The green logistics also takes into consideration social and environmental factors, and studies themes such as reverse logistics, waste management, and routing models (Sbihi and Eglese, 2007).

3.1. Vehicle Routing Problem definition

The routes travelled by the vehicles are an important part of the distribution systems and are object of several studies (Touati-Moungla and Jost, 2012). The Vehicle Routing Problem (VRP) is one of the main challenges of the distribution management areas (Cordeau *et al.*, 2002).

The VRPs are defined on graphs where the nodes typically represent clients and the arcs represent the connections between the clients. Considering that (Christofides *et al.*, 1981):

- The set $N = N_c \cup \{0\}$, where $N_c = \{1, \ldots, n\}$ is a set of n nodes that represent the clients and node 0 is the starting node and represents the central depot.
- The set $A = \{(i,j): i,j \in N \wedge i \neq j\}$ is the set of arcs (i,j) that represent the pairs of clients (i,j).
- To each client i: a determined quantity q_i of product must be delivered by a determined vehicle; the delivery of the quantity q_i to the client i represents a cost u_i.
- It is assumed a fleet of m identical vehicles, each with a similar capacity Q, that depart from the central depot (a sufficient large number of vehicles is assumed in order for a possible solution to exist).
- The cost of the shortest path between the pairs of clients i and j (*e.g.* distance or time) is given by a matrix $C = \{c_{ij}\}$.
- The total cost of each route traveled by each vehicle is calculated by summing the costs c_{ij} associated with each arc (i,j) and summing the costs u_i associated to the clients included in the route, and must be lower or equal than a pre-defined value T.
- The total demand satisfied in each route must not exceed Q.

- The objective of the VRP is determining one route for each vehicle in order to satisfy the demand of all the clients, minimizing the cost associated with to each arc of all the routes.

A VRP formulation can be found in Christofides *et al.* (1981).

3.2. VRP resolution methods

The VRP is a NP-hard problem which means that the optimal solution is only obtained for problems with few collection (or delivery) points (Cordeau *et al.*, 2002). Baldacci and Mingozzi (2009) present an example of solving a VRP through an exact resolution method.

However, the majority of USW VRPs cannot be solved through exact methods because of the complexity the collection systems (see, *e.g.*, Nuortio *et al.*, 2006; Makan *et al.*, 2011). It is important though to find solutions that are near the optimal. These solutions are found using heuristics, which aim at finding a good near optimal solution for specific problems.

The classical heuristics are divided in constructive and improvement heuristics. The most popular constructive heuristic is the Clarke and Wright (1962) savings algorithm. Its basic principle is obtaining cost savings by joining two separate routes in one route.

The savings algorithm is popular because of its solving speed and implementation simplicity, even though it is not the most precise one. Given the current importance of improvement heuristics, a simple scheme such as the savings algorithm is adequate to solve most of the problems (Laporte, 2007).

One of the most used improvement heuristics is the 2-Opt (Flood, 1956) in which each route is modified through the elimination of two arcs, resulting in two separate chains. The two chains are then connected again in the other possible way.

The heuristic methods are developed to solve specific problems and the solution of a new type of problem requires the development of a new heuristic. The metaheuristics are the answer to this limitation, and are general methods that provide the structure and guidelines to develop a specific heuristic that can be applied to a specific problem (Hillier and Lieberman, 2001). They include procedures from classical and improvement heuristics and can be classified in local search, population search and learning mechanisms. The explanation for each type of metaheuristic can be found in Laporte (2007).

One example of a local search algorithm is the tabu search (Glover, 1986). One example of a population search algorithm is the study of Tarantilis and Kiranoudis (2002). One example of a learning mechanism is the study of Mazzeo and Loiseau (2004).

Besides the previous methods, there has been a growing utilization of Geographic Information Systems (GIS) to solve VRPs. Nuortio *et al.* (2006) report that there are several studies where VRPs are solved using computers.

A GIS is a software tool that combines geographic information (*i.e.* location of an object) with descriptive information (*i.e.* characteristics of that object). The different information is organized in layers that can be combined in a digital map. Each layer is a distinct particularity of the map (*e.g.* a layer can represent all roads in one area).

For planning USW collection, GIS can improve efficiency and efficacy both economic and environmentally, by reducing travel times and distances, fuel consumption and pollutant emissions. In fact, GIS have been extensively used to study waste management systems (Chalkias and Lasaridi, 2011; ESRI, 2012).

4. Approaches to solve Amarsul's VRP

The present study aimed at solving Amarsul's VRP and obtaining recyclable glass waste collection routes that minimized separately the time spent and the distance travelled. Two different approaches were used for solving it and their results were compared.

The first approach was a GIS, namely the ArcGIS software. One example of the application of GIS to solve a VRP is the study of Tavares *et al.* (2009).

The second approach was the routePlanner, a Decision Support System (DSS) developed in this work, which had implemented the Clarke and Wright (1962) and the 2-Opt (Flood, 1956) heuristics. The Clarke and Wright (1962) algorithm was chosen for its solving speed and implementation simplicity (Laporte, 2007). Through this algorithm was obtained a first set of routes that solved Amarsul's VRP. These routes were then improved using the 2-Opt (Flood, 1956). An example of solving the VRP through the Clarke and Wright (1962) algorithm is the study of Makan *et al.* (2011). An example of improving routes through the 2-Opt heuristic is the study of Nuortio *et al.* (2006).

4.1. The Geographic Information System ArcGIS

The Amarsul VRP was solved using ArcGIS's Network Analyst which includes two options that can be used to create routes: the "New Vehicle Routing Problem" ("New VRP") which solves the VRP, and the "New Route" which finds the shortest path between a set of nodes.

The "New VRP" uses the tabu search heuristic (Glover, 1986) to solve the VRP and requires the insertion of the containers included in the circuit, the vehicles that can be used and the starting and unloading points available. In the Amarsul's case were used vehicles A and B (see characteristics in section 2), and the treatment plant was the only starting and ending point.

The calculation of the shortest path between a set of nodes using the "New Route" option only needs the set of containers and the collection sequence as inputs, once it uses Dijkstra's (1959) algorithm. The "New Route" can also rearrange the sequence provided by the user to improve the value of the objective function.

4.1.1. ArcGIS limitations

In ArcGIS the VRP is only solved using time as the minimization variable (ESRI, 2016). To use the distance as the minimization variable and surpass this limitation, the original database was modified, *i.e.* in the table that characterizes Barreiro's road network, the column containing the travel time of each road section was replaced by a column with the respective travel distances.

This modification did not change the fact that, for the internal ArcGIS algorithm, the distances (now included in the time column) corresponded to time. Taking this into consideration, for every vehicle stop with a service time associated (*i.e.* collecting a containers content and unloading the transported content at the treatment plant) the software tool added the service time values (*i.e.* 4.5 minutes for collection and 10 minutes for unloading) to the total distance travelled. This error was mitigated by not including the service times in the distance minimization routes, which generated routes that used only one vehicle as the 300 minutes constraint was not violated. The exception occurred in circuit B.

4.2. The Decision Support System routePlanner

The DSS concept is broad and its definition depends on the author. In the attempt of generalizing this concept, Druzdzel and Flynn (2002) proposed the following DSS definition: DSSs are "*interactive, computer-based systems that aid users in judgment and choice activities*".

According to Druzdzel e Flynn (2002) a DSS has three main components: 1) a database; 2) a data transformation model; 3) an intuitive user interface. In the routePlanner developed:

1. The database contains all the data about Amarsul's containers and fleet of vehicles;
2. The data transformation model are the VRP's solving heuristics, *i.e.* Clarke and Wright (1962) and 2-Opt (Flood, 1956);
3. The intuitive user interface is the interface between the user and the DSS.

These three components were integrated in a user-friendly system developed in Microsoft Excel using the VBA programming language.

5. Results

The results obtained through both approaches were analyzed using the following indicators:

- The improvement of the objective function was calculated through the Verified Improvement indicator;
- The used vehicle loading capacity previous to the discharge was calculated through the Used Capacity indicator;
- The work distribution between the vehicles was calculated in terms of:
  a) The containers serviced by each vehicle, using the Serviced Containers indicator;
  b) The distribution between both vehicles of the total time / distance of a circuit, using the Workload Distribution indicator.

Each indicator can be calculated as follows:

a) Verified Improvement (*VI*)

$$VI = \left[1 - \frac{\text{value of the objective function using method } x}{\text{value of the objective function using method } y}\right] \times 100 \text{, being } x \neq y \tag{1}$$

and $x, y \in$ {"*New VRP*", "*New Route*", Clarke & Wright, 2-Opt}

b) Used Capacity (*UC*)

$$UC = \left[\frac{\text{used capacity of vehicle z prior to the discharge at the treatment plant}}{\text{total waste transportation capacity of vehicle z}}\right] \times 100 \text{, where } z \in \{A, B\} \tag{2}$$

Note: For each circuit, the *UC* values presented for each vehicle are the average of the *UC* values of all the routes travelled by that same vehicle.

c) Served Containers (*SC*)

$$SC = \text{number of containers served by vehicle z, where } z \in \{A, B\} \tag{3}$$

d) Workload Distribution (*WD*)

$$WD = \left[\frac{\text{value of the objective function using Vehicle z}}{\text{total value of the objective function}}\right] \times 100 \text{, where } z \in \{A, B\} \tag{4}$$

The previous indicators allowed to compare directly the improvement in the objective functions, and the vehicle's usage efficiency.

5.1. The ArcGIS results

The waste collection routes were obtained through the "New VRP" option. However, the first comparison between ArcGIS and the routePlanner showed that, for some circuits, ArcGIS generated worst quality routes than the ones generated by the routePlanner (*i.e.* with worst values of minimized variables). Taking this into consideration there was a need to test if the "New VRP" routes were the best ones ArcGIS could generate. To test it, the sequences of containers of each route generated by the "New VRP" option were introduced in the "New Route" option and the algorithm was allowed to rearrange those sequences if it resulted in an improvement of the minimized variable values.

The results obtained through the "New VRP" option are compared with the results obtained using the "New Route" in sections 5.1.1 and 5.1.2. The *VI* indicator was calculated in order to compare which option generated the best routes, being used in the numerator the values from the "New Route" option and in the denominator the values of the "New VRP" option. The other indicators were calculated based on the "New VRP" option routes, because the "New Route" option is not practical for a daily use, as it represents a significant increase of the time spent by the user (who first needs to solve the VRP using the "New VRP" option, then needs to manually introduce each container of each route obtained, and only then can use the "New Route" option to rearrange the sequences) and it does not produce significantly better results than the "New VRP" option.

On the distance minimization routes ArcGIS only used vehicle B to collect and transport the waste. Taking this into consideration, the *SC* and *WD* indicators were not calculated. The *UC* indicator was still calculated because of its relevance for analyzing the vehicle's loading capacity usage efficiency. For the routes that minimized the time spent all the indicators were calculated in order to do a comprehensive analysis to the results obtained.

5.1.1. Time minimization results

Table 1 shows that the "New Route" option improved the routes for three of the five Amarsul circuits, when compared with the ones generated by the "New VRP" (*e.g.* the *VI* for circuit E was approximately 3%, which corresponds to a 4 minutes saving). Taking this into consideration it can be inferred that the results obtained through the “New VRP” algorithm can be improved by rearranging the collection routes’ sequences. However, the increase in complexity and the insignificant improvements associated with the routes rearrangement make the “New Route” option unviable for a daily use. It is important to refer, nevertheless, that using a simple algorithm such as the Dijkstra’s (1959) shortest path improved the results obtained by a more complex one (*i.e.* algorithm based on the tabu search metaheuristic (Glover,1986)).

Table 1 – Time minimization results obtained by the “New VRP” and by the “New Route” options of ArcGIS, and calculation of the *VI* indicator

Circuit	Used option		*VI* [%]
	“New VRP”	“New Route”	
	Time [min]	Time [min]	
A	156.81	156.19	0.40%
B	194.31	194.87	-0.29%
C	152.07	152.21	-0.09%
D	158.98	158.93	0.03%
E	131.94	128.01	2.98%

The analysis of the vehicle’s loading capacity usage efficiency, calculated through the *UC* indicator (see Table 2), shows that the loading capacity of vehicle A was used more efficiently than the capacity of vehicle B. For all the circuits, the capacity of vehicle A was used at more than or equal to 80% of its maximum value, whereas the capacity of vehicle B was used at 79% and 69% for circuits A and C, respectively.

The analysis of the work distribution between both vehicles shows that: vehicle B collected waste from more containers than vehicle A, except for circuit B; the distribution of the total collection time by both vehicles was approximately the same, except for circuit E, where vehicle B was used more often.

Table 2 – Calculation of the indicators *UC*, *SC* and *WD* for the time minimization routes obtained by the “New VRP” option of ArcGIS

Circuit	Vehicle	*UC* [%]	*SC* [nr. cont.]	*WD* [%]
A	A	80	20	48
	B	79	30	52
B	A	89	36	60
	B	84	28	40
C	A	98	29	51
	B	69	36	49
D	A	85	26	50
	B	95	43	50
E	A	99	14	29
	B	85	34	71

5.1.2. Distance minimization results

Similarly to the time minimization results, Table 3 shows a general improvement associated with rearranging the routes through the “New Route” option (the only exception was circuit B, in which vehicle A was also used). The *VI* ranged from 0.15% to 3.29%, with savings from 129 to 3141 meters.

The analysis of the vehicle’s loading capacity usage efficiency shows that vehicle B was used almost at its full capacity. For all circuits, the vehicle B capacity was used at more than or equal to 80% of its maximum value prior to the discharge at Amarsul’s treatment plant. This was the opposite of what happened in the time minimization, in which vehicle A was the one whose loading capacity was used in a more efficient way.

Table 3 – Distance minimization results obtained by the “New VRP” and by the “New Route” options of ArcGIS, and calculation of the *VI* and *UC* indicators

Circuit	Used option		*VI* [%]	*UC* [%]
	“New VRP”	“New Route”		
	Distance [km]	Distance [km]		
A	88.617	88.488	0.15%	93
B	137.018[1]	137.121[1]	-0.01%	44 (Vehicle A) / 84 (Vehicle B)[1]
C	89.390	88.646	0.83%	96
D	113.732	112.551	1.04%	80
E	93.582	92.441	1.22%	82

Note: (1) – The *UC* was calculated for vehicle A and vehicle B because, ArcGIS used vehicle B to collect waste from 5 containers.

5.2. The routePlanner results

The routePlanner allowed the user to obtain an initial set of good quality routes using the Clarke and Wright (1962) savings algorithm and then to improve these routes using the 2-Opt (Flood, 1956) heuristic. The results were analyzed by comparing the initial routes (obtained by the savings algorithm) with the improved routes (obtained by the 2-Opt). This comparison was made through the *VI* indicator, using in the numerator the values of the improved routes and in the denominator the values of the initial routes. The *VI* indicator corresponded then to the improvement percentage of using the 2-Opt heuristic over the routes obtained by the savings algorithm.

To compare the distance minimization routes of the routePlanner with those of the ArcGIS, the vehicle B was the only one used. Taking this into consideration, the indicators *SC* and *WD* were discarded, but the *UC* indicator was calculated to assess the vehicle's usage efficiency. For time minimization all the indicators were calculated to do a comprehensive result analysis.

5.2.1. Time minimization results

The analysis of the results of Table 4 shows that the routes generated by the 2-Opt (Flood, 1956) were more efficient than the routes generated by the Clarke and Wright (1962) algorithm. The *VI* ranged from 0.32% to 1.74%, corresponding to savings from 0.64 to 2.85 minutes. Even though not significant, these improvements did not require any additional user effort (*i.e.* the user only needed to select a check-box) or computational effort (*i.e.* the solving time is not increased).

Table 4 – Time minimization results obtained by the Clarke and Wright (1962) (C&W column) and by the 2-Opt (Flood, 1956) heuristics (C&W + 2-Opt column), and calculation of the *VI* indicator

Circuit	Used heuristic		*VI* [%]
	C&W	C&W + 2-Opt	
	Time [min]	Time [min]	
A	149.84	148.50	0.89
B	203.16	202.50	0.32
C	153.45	152.81	0.42
D	163,44	160,59	1,74
E	129,07	128,43	0,50

The capacity of vehicle B was more efficiently used than vehicle A (see Table 5), once it was always used at more than or equal to 73% of its maximum value (being equal to 99% for the majority of the circuits, which represents a full truck load prior to discharge). The vehicle A had a lower *UC*, *e.g.* 53% of its total capacity for circuit A.

The analysis of the work distribution between both vehicles (see Table 5) shows that vehicle B always collected waste from a higher number of containers than vehicle A. However, there was an approximate equal division of the total time spent in each circuit by both vehicles, even though vehicle B was always slightly more used. Remember that vehicle B has the highest capacity, which can represent less time spent in the collection routes once it needs less visits to discharge the content at the treatment plant.

Table 4 – Calculation of the indicators *UC*, *SC* and *WD* for the distance minimization routes obtained by the 2-Opt (Flood, 1956) improvement heuristic

Circuit	Vehicle	*UC* [%]	*SC* [nr. cont.]	*WD* [%]
A	A	53	9	42
	B	99	41	58
B	A	99	21	37
	B	73	43	63
C	A	58	27	42
	B	99	38	58
D	A	79	25	46
	B	99	44	54
E	A	99	14	36
	B	86	34	64

5.2.2. Distance minimization results

Similarly to the time minimization results, the routes improved by the 2-Opt (Flood, 1956) heuristic were always better than the initial routes obtained by the Clarke and Wright (1962) savings algorithm (see Table 6). The *VI* ranged from 0.20% to 1.44% with savings from 184 to 1705 meters. Also here, these improvements did not require an increase in user or computational effort.

Regarding the vehicle's loading capacity usage efficiency, the vehicle B capacity was used near to its maximum value for circuits A, B and C and more than or equal to 80% for circuits D and E.

Table 5 – Distance minimization results obtained by the Clarke and Wright (1962) (C&W column) and by the 2-Opt (Flood, 1956) heuristics (C&W + 2-Opt column), and calculation of the *VI* and *UC* indicators

Circuit	Used heuristic		*VI* [%]	*UC* [%]
	C&W	C&W + 2-Opt		
	Distance [km]	Distance [km]		
A	89.265	88.060	1.35	93
B	118.361	116.656	1.44	92
C	91.059	90.875	0.20	96
D	95.085	94.441	0.68	80
E	88.825	88.171	0.74	82

5.3. Comparison between the ArcGIS results and the routePlanner results

The comparison of the results produced by both approaches followed the same methodology of sections 5.1 and 5.2. The values compared were those obtained through ArcGIS's "New VRP" option and those obtained through the routePlanner's 2-Opt (Flood, 1956) heuristic. The explanation for choosing the "New VRP" option routes can be found in section 5.1. The 2-Opt improved routes were chosen because they were the most efficient ones and did not require any additional effort by the user.

Initially were compared the time minimization routes, by calculating all the indicators defined in section 5. Then were compared the distance minimization routes, not being calculated the *SC* and *WD* indicators because ArcGIS only used vehicle B to collect and transport the waste (see the explanation in section 4.1.1).

5.3.1. Time minimization results

Table 7 does not allow drawing an immediate conclusion about which is the best tool for solving Amarsul's VRP, as for some circuits the routes generated by the routePlanner were more efficient than the ones generated by ArcGIS, and for other circuits the opposite happened. However, when considering the waste collection during a one-year period, the routePlanner generated slightly more efficient routes – the total *VI* was 0.11% – in comparison to ArcGIS (approximately 14 minutes). The total *VI* was calculated based on the collection of the containers' waste during a one-year period, considering the following assumptions: the containers of circuits A, B and C are collected each 3 weeks; the containers of circuits D and E are collected each 4 weeks; the number of weeks in one year is equal to 52.

Table 6 – Time minimization results obtained through ArcGIS's "New VRP" option and through routePlanner's 2-Opt (Flood, 1956) heuristic, and calculation of the *VI* indicator

Circuit	Number of collection times during one year	Used approach		*VI*[1] [%]
		ArcGIS	routePlanner	
		Time [min]	Time [min]	
A	17.3	156.81	148.50	5.30
B	17.3	194.31	202.50	-4.21
C	17.3	152.07	152.81	-0.49
D	13	158.98	160.59	-1.01
E	13	131.94	128.43	2.66
Total per year	-	12196.23	12184.15	0.11

Note: (1) – For the calculation of the *VI* indicator were used in the numerator the values of the routes generated by the routePlanner and in the denominator the values of the routes generated by the ArcGIS.

Table 8 shows that routePlanner always used more intensively one of the vehicles in all the circuits. For this vehicle the used capacity was always close to its maximum value, being the other vehicle used more in a more inefficient way. This did not happen in the ArcGIS routes, where the capacity of both vehicles was similarly used. The analysis of the work distribution between both vehicles also shows a more equal distribution in the ArcGIS routes than in the routePlanner routes (Table 8 shows similar *SC* and *WD* for both vehicles in the ArcGIS routes). Example: for circuit A, the ArcGIS generated routes where vehicle A served 20 containers and vehicle B served 30 containers. For the same circuit, the routePlanner generated routes where vehicle A served 9 containers and vehicle B served 41 containers.

Table 7 – Calculation of the indicators *UC*, *SC* and *WD* for the time minimization routes generated through ArcGIS and routePlanner

Circuit	Used approach	*UC*		*SC*		*WD*	
		Vehicle A [%]	Vehicle B [%]	Vehicle A [nr. cont.]	Vehicle B [nr. cont.]	Vehicle A [%]	Vehicle B [%]
A	ArcGIS	80	79	20	30	48	52
	routePlanner	53	99	9	41	32	68
B	ArcGIS	89	84	36	28	60	40
	routePlanner	99	73	21	43	37	63
C	ArcGIS	98	69	29	36	51	49
	routePlanner	58	99	27	38	42	58
D	ArcGIS	85	95	26	43	50	50
	routePlanner	79	99	25	44	47	53
E	ArcGIS	99	85	14	34	29	71
	routePlanner	99	86	14	34	36	64

5.3.2. Distance minimization results

The analysis for the distance minimization results is more conclusive than the one for the time minimization results. Except for circuit C (where the ArcGIS generates better routes) and for circuit B (which was not compared – see note 2 in Table 9), the routePlanner generated better routes than ArcGIS. The *VI* ranged from 0.63% to 16.96% with savings from 557 to 19291 meters. Globally, the analysis of the collection of the containers of the circuits A, C, D and E during a one-year period (see assumptions in section 5.3.1), showed that the routePlanner improved ArcGIS routes by 5.28% which corresponds to a saving of about 305 km.

Both the ArcGIS and the routePlanner showed, however, a similar efficiency in terms of the usage of the vehicle B loading capacity. For all the circuits, both tools generated routes in which the average used capacity was always more than or equal to 80% of its maximum value.

Table 8 – Distance minimization results obtained through ArcGIS's "New VRP" option and through routePlanner's 2-Opt (Flood, 1956) heuristic, and calculation of the *VI* and *UC* indicators

Circuit	Number of collection times during one year	Used approach		*VI*[1] [%]	*UC*	
		ArcGIS	routePlanner		ArcGIS [%]	routePlanner [%]
		Distance [km]	Distance [km]			
A	17.3	88.617	88.060	0.63	93	93
B	17.3	137.018[1]	116.656[1]	N.A.[2]	N.A.[2]	
C	17.3	89.390	90.875	-1.66	96	96
D	13	113.732	94.441	16.96	80	80
E	13	93.582	88.171	5.78	82	82
Total p/ year (without circuit B)	-	5780.537	5475.496	5.28	-	

Notes: ([1])Numerator: values of the routes generated by routePlanner; Denominator: values of the routes generated by ArcGIS; ([2])ArcGIS also used vehicle A to collect the content of 5 containers. This makes the results incomparable, once the routePlanner only allows the intensive usage of one vehicle or of both.

6. Conclusions and future work

Considering the collection and transportation system of Amarsul and the characteristics of both approaches, the global results analysis allowed to conclude that the routePlanner provides a higher added value than the ArcGIS (*i.e.* the sum of the times and distances of all the routes generated was smaller for the routePlanner than for the ArcGIS). It is important to refer, though, that the routePlanner was tailor made for Amarsul (even though it can be customized to other cases).

The best solution for Amarsul would be, however, to use simultaneously both approaches as for some circuits the ArcGIS generates more efficient routes and for other circuits the opposite happens. In the future, the characteristics of the circuits' that influence the ArcGIS results should be studied. The reason why the “New VRP” routes are not always the best ones that ArcGIS generates should also be studied.

The implementation in a DSS of a more complex heuristic than the Clarke and Wright (1962) algorithm is also suggested. A tabu search (Glover, 1986) metaheuristic would be of special interest in order to allow a direct comparison between routePlanner and ArcGIS.

Different objective functions should also be considered in the future, *e.g.* the minimization of pollutant gases emissions, considering the growing concerns with environmental aspects.

A last aspect that can be studied is the update of the fleet of collection vehicles, namely through the introduction of more efficient collection vehicles. An analysis of the economic viability associated with this update should be performed (*e.g.* net present value, internal rate of return and payback period), also accounting the reduction of the emission of pollutant gases generated.

References

Amador, J. (2010). Energy Production and Consumption in Portugal: Stylized Facts. Economic Bulletin - Volume 16, Number 2 (pp. 69–83). Lisbon, Portugal: Banco de Portugal.

Baldacci, R., Mingozzi, A. (2009). A unified exact method for solving different classes of vehicle routing problems. Mathematical Programming, 120(2), 347–380.

Chalkias, C., Lasaridi, K. (2011). Benefits from GIS Based Modelling for Municipal Solid Waste Management. In M. S. Kumar (Ed.), Integrated Waste Management - Volume I (pp. 417–436). Rijeka, Croatia: InTech.

Christofides, N., Mingozzi, A., Toth, P. (1981). Exact Algorithms for the Vehicle Routing Problem, based on Spanning Tree and Shortest Path Relaxations. Mathematical Programming, 20(1), 255–282.

Clarke, G., Wright, J. W. (1962). Scheduling of Vehicles from a Central Depot to a Number of Delivery Points. Operations Research, 12(4), 568–581.

Cordeau, J-F., Gendreau, M., Laporte, G., Potvin, J.-Y., Semet, F. (2002). A Guide to Vehicle Routing Heuristics. Journal of the Operational Research Society, 53(5), 512–522.

Dijkstra, E. W. (1959). A Note on Two Problems in Connexion with Graphs. Numerische Mathematik, 1(1), 269–271.

Druzdzel, M., Flynn, R. R. (2002). Decision Support Systems. To appear in Encyclopedia of Library and Information Science (2nd Edition), Allen Kent (ed.), New York: Marcel Dekker, Inc., 2002.

ESRI (2012) What is GIS?. Redlands, USA: ESRI.

ESRI (2016) Vehicle routing problem analysis - Time attribute.

Flood, M. M. (1956). The Travelling-Salesman Problem. Operations Research, 4(1), 61–75.

Gaines, L., Vyas, A., Anderson, J. L. (2006). Estimation of Fuel Use by Idling Commercial Trucks (Paper No. 06-2567). Argonne, USA: Center for Transportation Research - Argonne National Laboratory.

Glover, F. (1986). Future paths for integer programming and links to artificial intelligence. Computers & Operations Research, 13(5), 533–549.

Hillier, F. S., Lieberman, G. J. (2001). Introduction to Operations Research (7th Edition). New York, USA: McGraw-Hill.

Laporte, G. (2007). What You Should Know about the Vehicle Routing Problem. Naval Research Logistics, 54(8), 811–819.

MA (1997). PERSU - Plano Estratégico dos Resíduos Sólidos Urbanos. Lisboa, Portugal: Ministério do Ambiente - Instituto Nacional de Resíduos.

Makan, A., Malamis, D., Assobhei, O., Loizidou, M., Mountadar, M. (2011). Solid waste management: case of collection and Vehicle Routing Problem in the city of Azemmour, Morocco. International Journal of Management Science, 6(4), 247–255.

MAOTDR (2007). PERSU II - Plano Estratégico para os Resíduos Sólidos Urbanos (Primeira). Lisboa, Portugal: Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional.

Mazzeo, S., Loiseau, I. (2004). An Ant Colony Algorithm for the Capacitated Vehicle Routing. Electronic Notes in Discrete Mathematics, 18, 181–186.

Nguyen, T. T., Wilson, B. G. (2010). Fuel consumption estimation for kerbside municipal solid waste (MSW) collection activities. Waste Management & Research, 28(4), 289–297.

Nuortio, T., Kytöjoki, J. J., Niska, H., Bräysy, O. (2006). Improved route planning and scheduling of waste collection and transport. Expert Systems with Applications, 30(2), 223–232.

Sbihi, A., Eglese, R. W. (2007). Combinatorial optimization and Green Logistics.4OR, 5(2), 99–116.

Tarantilis, C. D., Kiranoudis, C. T. (2002). BoneRoute: An adaptive memory based method for effective fleet management. Annals of Operations Research, 115(1), 227–241.

Tavares, G., Zsigraiova, Z., Semiao, V., Carvalho, M. G. (2009). Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling. Waste Management, 29(3), 1176–1185.

Tchobanoglous, G. (2003). Solid Waste Management. In J. A. Salavato, N. L. Nemerow, & F. J. Agardy (Eds.), Environmental Engineering (5th Edition, pp. 755–888). Hoboken, USA: John Wiley & Sons, Inc.

Touati-Moungla, N., Jost, V. (2012). On green routing and scheduling problem. Research Report published in HAL (ref. hal-00674437).