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A case study of fuel savings through optimisation of MSW transportation routes

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A case study of fuel savings through optimisation of MSW transportation routes

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Abstract

Purpose – The high costs of collection and transportation of municipal solid waste (MSW) on the overall waste management budget (sometimes more than 75 per cent) makes it an issue to be urgently addressed for improvement. The paper aims to focus on the optimisation of routing networks for waste collection/transportation.

Design/methodology/approach – The paper proposes herein the application of geographic information system (GIS) 3D route modelling for waste collection/transportation to optimise the route according to the minimum fuel consumption criterion to different municipalities of the island of Santo Antao of Cape Verde.

Findings – The optimisation for the lowest fuel consumption yields 52 per cent savings in fuel, when compared to that for the shortest distance, even travelling a 34 percent longer distance, which shows the importance of considering simultaneously the relief of the territory and the lowest fuel consumption criterion when optimising vehicle routes.

Practical implications – With such a supporting decision tool savings in fuel are huge, the efficiency of management systems is improved and the environmental impact during daily operation is reduced. The GIS 3D route modelling takes into account the effects of both the road inclination and the vehicle load.

Originality/value – The originality of the work lies in the chosen approach. To optimise vehicle routes the criterion of minimum fuel consumption rather than the commonly used shortest distance is used, since fuel consumption is the factor reflecting actual costs relative to MSW management.

Keywords Modelling, Land transport, Waste handling, Automotive fuels

Paper type Case study

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1. Introduction

Systems for municipal solid waste management (MSWM) are very complex since they deal with sustainable solutions at all the waste paths, from its generation at source until its final disposal. Therefore, a rational management is undoubtedly essential to sustainable development, particularly in developing countries where the population growth has been intense and the huge amounts of produced waste are being disposed at open and uncontrolled landfills. This is the case of Cape Verde, the country that is studied herein.

Besides, the negative impact of untreated waste on public health and on public concern, which focused the attention of engineers and scientists on the quest for waste management solutions viewing the prevention of undesired environmental effects, economy plays also an important role on this activity. In fact, collection and transportation of waste can absorb as much as 75 per cent of the municipalities' MSWM budget that are usually the institutions responsible for such activities.

One of the heavy costs present in MSWM systems is the fuel price and its consumption is inevitably associated with undesired pollutants emissions. Therefore, the minimisation of fuel consumption to perform waste collection and transportation to its treatment or final disposal brings enormous savings and environmental benefits.

Most works reporting optimal routing assessments for waste collection and transportation are based on the minimisation of the travelled distance. Morrissey and Browne (2004) pointed out the first of such models that dealt with specific aspects of the problem, as the vehicle routing of Truitt *et al.* (1969) or the transfer station sitting studied by Esmaili (1972). While some authors adapted simulation modelling for optimal solid waste collection, like Baetz (1990) and Bhat (1996), others, such as Clark and Gillean (1974), used analytical approaches. Optimisation recurring to operational research methodologies has been applied by several authors, as Cordeau *et al.* (2002), Badran and El-Haggar (2006) and Simonetto and Borenstein (2007).

Furthermore, as a natural outcome of research in this area, it has been recognised that effective decision making in the field of management systems requires the implementation of vehicle routing techniques capable of taking advantage of new technologies such as the geographic information system (GIS) Bodin and Levy (1981), Keenan (1998) or Armstrong and Khan (2004). Since routing models make extensive use of spatial data, GIS can provide effective handling, displaying and manipulation of such geographical and spatial information. For example, Ghose *et al.* (2006) proposed a model for the system of municipal solid waste (MSW) collection that provides planning for distribution of collection bins, load balancing of vehicles and generation of optimal routing based on GIS. The application of route generation heuristics in a GIS context was performed by Viana (2006), focusing on the vehicle routing problem (VRP) applied to the optimisation of solid waste collection systems.

Some additional factors, such as the vehicle speed, the waste bins lifting, the waste compacting or the traffic disturbances have also been taken into account. Sonesson (2000) presented a model to calculate the time and energy consumption during waste collection, which is a function of the travelled distance, extra time and fuel consumed during hauling, stopping and compacting of waste. Supporting their study on GIS tools for road transport and on real-time information about traffic disturbance events, Ericsson *et al.* (2006) proposed a model to estimate the potential reduction of fuel consumption through route optimisation for the lowest total fuel consumption (TFC) rather than for the shortest time consumed or the shortest distance travelled.

It must be mentioned that the vehicle engine performance and efficiency are also strongly influenced by the roads slope, resulting in a variation of the engine power demand, yielding different amounts of fuel consumption and emissions. This makes mandatory the accounting of roads slope when determining the fuel consumption during waste collection and transportation. This issue is studied in the present work. For that, the model developed by Tavares *et al.* (2007) that establishes optimal routes for waste collection and transportation with the minimum fuel consumption is used herein. The model is based on GIS tools and takes into consideration the relief of the terrain represented by the slope of the roads and the effect of the vehicle load to calculate the fuel consumption. Based on such model, it is possible to establish optimal routes for waste collection and transportation defined as those that minimise the fuel consumption, not necessarily corresponding to the shortest travelled distance.

The previously mentioned model is applied herein to define the viability of MSW collection and transportation at Santo Antao, one of the islands of the Cape Verde archipelago.

2. Case study

2.1 Demographic and geographic aspects

The MSW treatment at Cape Verde and more specifically at the island of Santo Antao was selected as the case study of the present research. The Republic of Cape Verde is an archipelago located in the Macaronesia eco-region of the North Atlantic Ocean, 500 km off the western coast of Africa. It consists of ten islands, distributed as shown in Figure 1. The population of less than half million is spread over nine islands. The

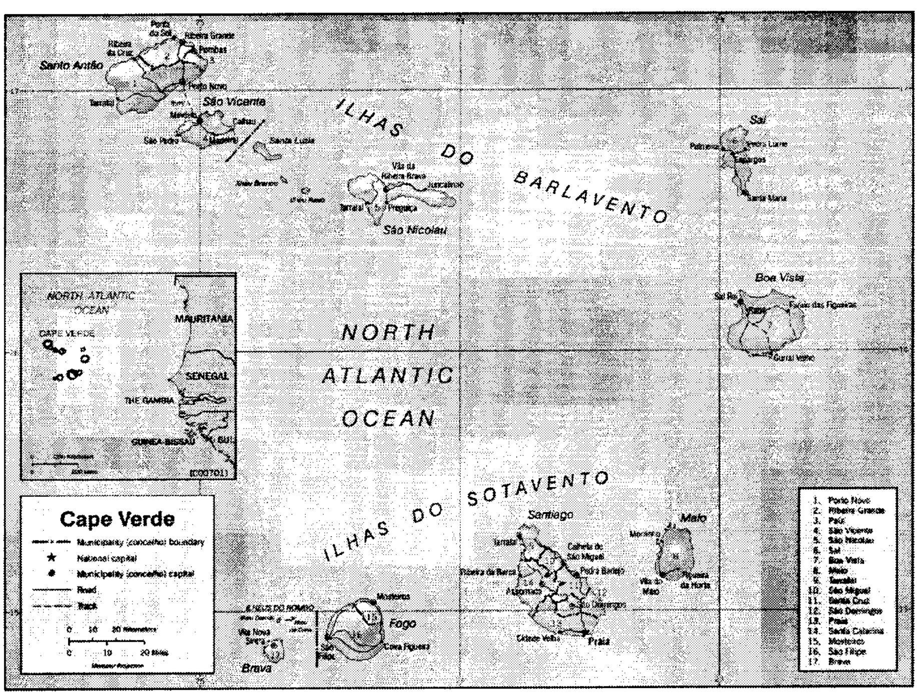


Figure 1.
Situation map of Cape Verde

largest and most populated island is Santiago, where the capital Praia is located. In the last decades, due to larger work opportunities, there has been an average annual growth rate of 2.4 per cent (INE, 2007) making of Cape Verde a developing country. Santo Antao is the westernmost island in Cape Verde and the second largest of the archipelago with 779 km^2 of a land area and with around 49,000 inhabitants. The island is entirely made up of volcanic matter. The southeast part of the island has an arid climate, while the northwest one has relatively normal precipitation. It results in an interesting combination of grass, bush, and forest covered areas along with dry land.

It should be mentioned that Santo Antao is the most hilly island of Cape Verde (the highest point is Topo da Coroa reaching a height of 1979 m over the sea level, located at the western part of the island) and is characterised by areas with considerable variations of the relief of the terrain resulting in significant gradients of the path roads.

The territory of Santo Antao Island is divided into three municipalities, Ribeira Grande, Paul and Porto Novo. Ribeira Grande covers some 21 per cent of the total island area with a number of inhabitants around 21,900. Porto Novo comprises around 67 per cent of the island area with one-third of the total population.

The Paul municipality is the smallest one and the majority of the population is rural. The main income of Santo Antao comes from trade in the urban centres of Ribeira Grande and Porto Novo, tourism and agriculture in the rural areas.

2.2 Waste management

Generated waste amounts increased considerably as a result of the demographic growth, tourism and other economic activities at Cape Verde. Despite the efforts for actions at governmental and municipal levels, there is still evident lack of development plans, the existing waste management being rather poor and characterised by inefficient collection systems.

The collected waste is disposed to uncontrolled open landfills with subsequent burning for volume reduction without any material or energy recovery, which results in direct negative impacts as far as the environment and population health are concerned. Therefore, the establishment of an integrated and well functioning waste management system that guarantees proper treatment and disposal of MSW represents a great challenge for Cape Verde.

Prospectively, there is a project in progress for thermal treatment of MSW by incineration. It is expected that the plant capacity will allow for the treatment of the waste collected from all the municipalities at Santiago Island together with those of other islands of Cape Verde. Considering this broad integration of MSWM of the entire archipelago, the present study focuses on the MSW collection and transportation from the municipalities of Santo Antao to a transfer station situated near Porto Novo, the port of the island. From there the waste is shipped to Santiago.

At Santo Antao there is no selective collection of MSW. Moreover, collection is performed in urban centres and some rural localities. In the towns small plastic bins with 220 l capacity and 800 l metallic bins are used. Industry and trade ensure their own waste collection and transportation directly to landfills. Waste is collected six days per week in the urban areas and two or three times per week in the rural areas. The final destinations of the collected waste are open and uncontrolled municipal landfills, where the waste is sometimes burnt and covered by soil and no further treatment takes place.

3. Methodology and modelling

Following the anticipated development of the MSWM system at Cape Verde mentioned above, the present study deals with the application of the GIS 3D modelling (Tavares *et al.*, 2007) to determine the optimal routing network minimising the fuel consumption for the waste transportation from the municipalities of Santo Antao to a transfer station located at the port of Porto Novo.

The methodology used in this work comprises three phases. Phase 1 establishes the 3D road network of Santo Antao, starting from the existing 2D road network with recourse to *ArcGIS 3D Analyst*. Phase 2 calculates the fuel consumption factors (FCFs) for the entire 3D road network. Phase 3 performs the optimisation of MSW transportation for minimum fuel consumption with recourse of *ArcGIS Network Analyst*.

3.1 The model of the terrain and the road network – Phase 1

In order to ensure a realistic representation of the studied situation, in this work is used a 3D model of the entire island of Santo Antao based on a digitised map provided in CAD files. Such 3D model is generated as polylines based on contour lines that reflect the actual relief of the terrain. Then, the 3D road network is generated from both the 2D road network and the terrain model complying with the road gradients. The present methodology makes possible the generation of road networks in the appropriate form allowing for the calculation of all inclinations of each road segment, which permits to determine the fuel consumption for both road directions (uphill and downhill). The 3D digital model and the road network obtained are presented in Figure 2, where the large variability of the relief can be observed.

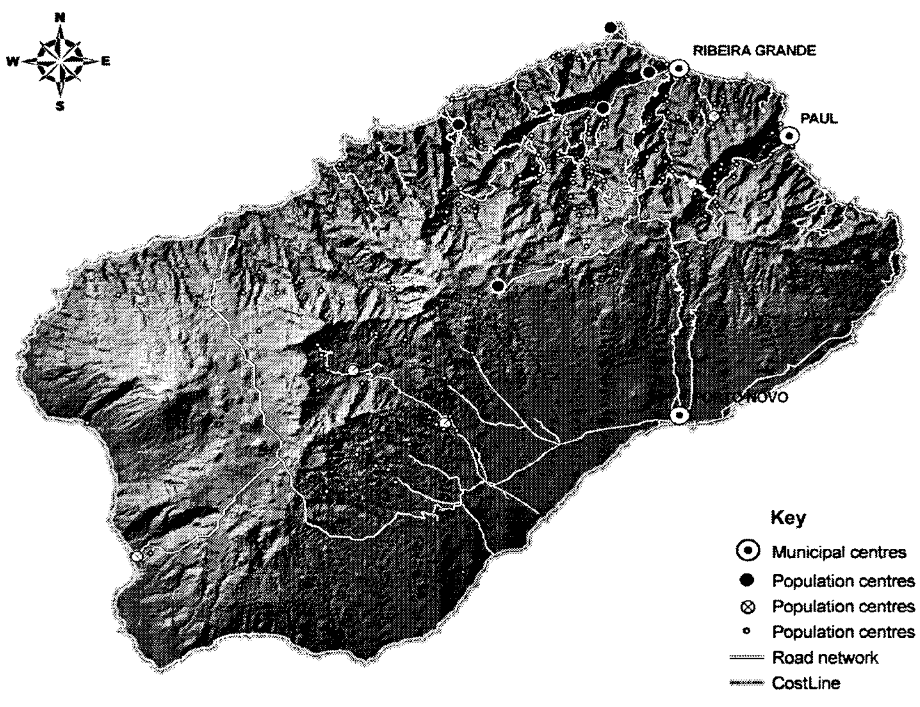


Figure 2.
3D digital model of Santo Antao island with the road network and the location of the population centres

3.2 Calculation of actual fuel consumption – Phase 2

Fuel consumption during waste collection and transportation is influenced by the travelled distance and by the actual operation conditions of a given vehicle. These effects are incorporated in the model through the methodology established by Ntziachristos and Samaras (2000) in COPERT, which is a computer programme to calculate emissions from transport vehicles on road. Besides considering specific vehicle parameters, the methodology also takes into account different driving conditions, namely the type of the driving situation, the vehicle load and the road gradient.

The type of trucks used for waste collection and transportation in Cape Verde are classified by COPERT in the category of *diesel heavy duty vehicles (from 7.5 to 16 t)* and the *EURO III* legislation class (European Commission, 1999) are utilised. To start with, a basic FCF (g/km) is assumed to be only speed dependent and different mean driving speeds can be considered according to diverse driving performances. Then, for heavy duty vehicles as those studied herein, it is necessary to account for the effect of the vehicle load and road gradient. For that, corrections are applied to the basic FCF in the form of a load correction factor and a gradient correction factor.

The gradient of a road increases, when positive, or decreases, when negative, the resistance of a vehicle to traction. Therefore, and because of their large masses, the power employed during the driving is the decisive parameter for the fuel consumption. To account for the road slope, the gradient correction factor calculated as polynomial functions of the mean speed of the vehicle for each vehicle weight and gradient class, valid for road slopes between −6 per cent and +6 per cent (Ntziachristos and Samaras, 2000), were fitted to an exponential function (Tavares *et al.*, 2007), so that a broader interval of steeper road slopes (−15 per cent to +15 per cent) could be considered. It should be mentioned that the length of each road segment depends on the road gradient and has a specific FCF associated to it, which makes possible the accounting for the road inclination in the fuel consumption calculation. This fuel consumption for a certain travelled distance is calculated for both directions (uphill and downhill). Then, the TFC for a given route (g) is expressed as the sum of the fuel consumptions on all the route arcs. The route arc fuel consumption is calculated, in turn, as the sum for all the segments contained in the arc of the products of the FCF of each segment by its length.

Once calculated, the fuel consumption value for each route arc is stored in the spatial data base to be used later during the route solver procedure that searches for the route with minimum fuel consumption.

3.3 Optimisation of vehicle routing – Phase 3

The efficiency of a management system that is able to solve problems related to vehicles circulation in road networks can be measured through its capacity to obtain optimised routes. For a system of MSW transportation, this consists of generating an optimal route for a given vehicle so that the value of the selected cost criterion is minimised.

For the calculation of the optimal routing, the model used herein makes recourse to *ESRI's* programs *ArcGIS*, *ArcInfo* and *Network Analyst* extension, and it finds the minimum defined impedance path through a network.

In order to compare solutions and clarify the potential of the present methodology, the routes are optimised regarding either the lowest fuel consumption or the shortest distance. The results are presented and discussed below.

4. Results and discussion

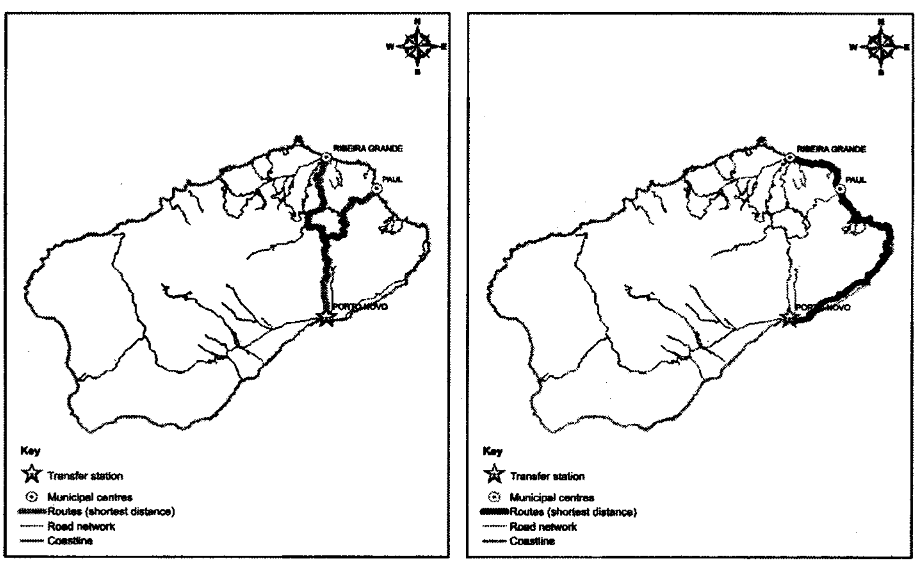
The above described modelling is applied to study and analyse the transportation of MSW at the island of Santo Antao, Cape Verde. Two different waste operations at diverse distance scales are considered. First, it is studied the global scale for long distance transportation of waste from Ribeira Grande and Paul directly to the transfer station situated near the port at Porto Novo. Then, for shorter distances travelled, it is analysed the local scale representing the collection of waste inside the selected rural area of the Ribeira Grande municipality.

Trucks with 12 t of capacity are considered for waste collection and transportation and the average vehicle speed is assumed to be 20 km/h. While for the entire waste collection operation (local scale) the vehicle is considered to have an average load of 50 per cent of the maximum load, for the case of waste transportation to the transfer station (global scale) it is assumed a full vehicle load on the way to and an empty vehicle on the way back.

4.1 Long distance transportation

The results obtained for the waste transportation case, the global scale, are shown in Figure 3.

As it can be noticed from Figure 3, totally different routes are defined according to the optimisation criterion applied. While routes passing the central hilly part of the island are chosen by the model when optimisation for the shortest distance is performed (Figure 3(a)), the optimised paths for the minimum fuel consumption follow the coastal line, since this road has a moderate variability of the elevation (Figure 3(b)).



(a) (b)

Figure 3.
A spatial distribution of the municipal centres and the location of the transfer station with the optimised MSW transportation routes

Notes: (**a**) using the shortest distance as objective; (**b**) using the lowest fuel consumption as objective

The numerical results for this case exhibiting fuel consumptions and distances travelled for both the way to and the way back are presented in Table I. When the optimisation criterion was switched from the shortest distance to the lowest fuel consumption an overall reduction in fuel consumption by 52 per cent was achieved (from 125,471 to 60,564 g per return trip) in spite of the increase observed for the distance travelled by 34 per cent (from some 104 to 140 km per return trip).

Because of the relief characteristics of Santo Antao island (yielding significant road gradients), the average vehicle speed was previously limited to 20 km/h. Under such condition, the best route obtained was the coastal one (see Figure 3(b)). With such defined route, the effect of the full loaded vehicle speed on the fuel consumption was then performed. Figure 4 shows the results of fuel consumptions for vehicle speeds ranging from 15 to 50 km/h.

As it can be observed, increasing the speed up to 150 per cent (from 20 to 50 km/h) can lead to additional fuel savings up to 36 per cent (reduced from 18.5 to 11.8 kg).

Table I. Results for the optimised waste transportation route from the municipal centres of Santo Antao to the transfer station (Porto Novo)

Vehicle return trip (Municipal centre – transfer station)	Shortest distance: Total distance (m/trip)	Shortest distance: Total fuel consumption (g/trip)	Lowest fuel consumption: Total distance (m/trip)	Lowest fuel consumption: Total fuel* consumption (g/trip)	Difference: Distance travelled (m/trip)	Difference: Fuel consumed (g/trip)
Ribeira Grande	54,762	64,764	78,811	32,536	+24,048	−32,228
Paul	49,112	60,707	60,820	28,029	+11,708	−32,678
Sum	103,874	125,471	139,631	60,564	+35,756	−64,907
Difference (per cent)					+34	−52

Optimisation criterion

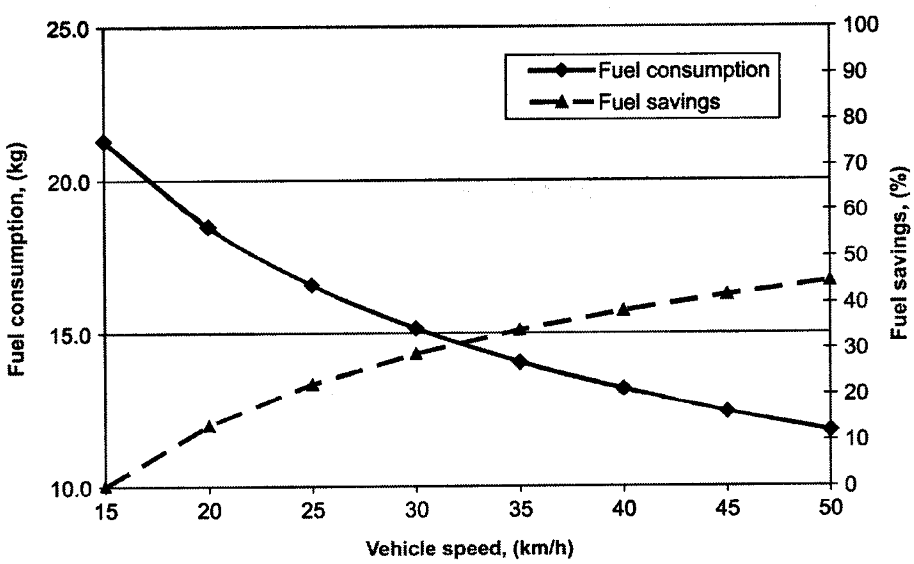


Figure 4. Effect of the full loaded vehicle average speed on fuel consumption travelling from Ribeira Grande to the transfer station by the coastal route

4.2 Short distance collection

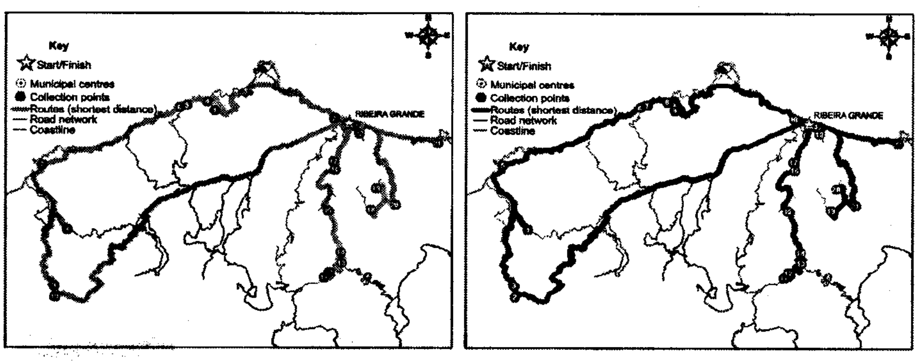
The results obtained for the waste collection, the local scale, when the route is solved for the shortest distance is shown in Figure 5(a) while that optimised for the lowest fuel consumption is displayed in Figure 5(b). Although there is practically no change in the travelled distance, the direction and sequence of the visited collection points taken by the truck is quite different (clockwise or anticlockwise). When optimising the collection route for the shortest distance, the model is insensitive to road gradients. In opposition, during the optimisation for the lowest fuel consumption the model avoids steep ascending roads, choosing different paths that ensure the lowest fuel consumption, even when the travelled distance is longer. Table II shows the numerical results obtained for the optimised waste collection routes shown in Figure 5(a) and (b).

As it can be seen, the significant amount of 9 per cent (from 80,609 to 73,646 g) in fuel savings is obtained when switching the route optimised for the shortest distance with that optimised for lowest fuel consumption, even with a slightly longer travelled distance (134 m).

The previous results evidence that both the relief of the terrain and the route optimisation through fuel consumption minimisation are important factors for the management of waste transportation vehicles.

5. Conclusions

The objective of the present work was to make evident the importance of considering the terrain relief, and thus the effect of the roads gradients, on fuel consumption during



(a) (b)

Figure 5.
A spatial distribution of the collection points in the selected rural area of the Ribeira Grande municipality with the optimised MSW collection routes

Notes: **(a)** using the shortest distance as objective; **(b)** using the lowest fuel consumption as objective

Table II.
Results for the optimised waste collection route for the rural area of Ribeira Grande

	Calculated parameters	
Optimisation criterion	Distance travelled (m)	Fuel consumed (g)
The shortest distance	78,626	80,609
The lowest fuel consumption	78,760	73,646
Difference (%)	+134	−6963
	+0.2	−9

waste collection and transportation by applying the 3D GIS modelling to optimise routes for vehicles according to the criterion of the lowest fuel consumption.

The application of the model to the selected case study of the island of Santo Antao in Cape Verde yielded optimal routes for the transportation of waste from the municipalities of Ribeira Grande and Paul to the transfer station (global scale) and for the waste collection at the rural area of Ribeira Grande (local scale) that confirmed the importance of taking into account the terrain relief when calculating the fuel consumption. For the different scale applications of the model, local and global, significant savings in fuel of 9 per cent and 52 per cent, respectively, were obtained when shifting from the shortest distance criterion to the lowest fuel consumption one.

These results clearly show the relevance of optimising vehicle routing for MSW collection and transportation according to the minimum fuel consumption criterion, rather than the commonly used shortest distance or time. This becomes particularly relevant in the cases where significant road gradients exist.

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