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Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling

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ABSTRACT

Collection of municipal solid waste (MSW) may account for more than 70% of the total waste management budget, most of which is for fuel costs. It is therefore crucial to optimise the routing network used for waste collection and transportation. This paper proposes the use of geographical information systems (GIS) 3D route modelling software for waste collection and transportation, which adds one more degree of freedom to the system and allows driving routes to be optimised for minimum fuel consumption. The model takes into account the effects of road inclination and vehicle weight. It is applied to two different cases: routing waste collection vehicles in the city of Praia, the capital of Cape Verde, and routing the transport of waste from different municipalities of Santiago Island to an incineration plant. For the Praia city region, the 3D model that minimised fuel consumption yielded cost savings of 8% as compared with an approach that simply calculated the shortest 3D route. Remarkably, this was true despite the fact that the GIS-recommended fuel reduction route was actually 1.8% longer than the shortest possible travel distance. For the Santiago Island case, the difference was even more significant: a 12% fuel reduction for a similar total travel distance. These figures indicate the importance of considering both the relief of the terrain and fuel consumption in selecting a suitable cost function to optimise vehicle routing.

1. Introduction

Daily human activity creates huge amounts of waste, particularly in urban areas. The impact of waste on public health has prompted engineers and scientists to explore waste management solutions with more favourable environmental footprints. As a consequence, municipal solid waste management systems (MSWMS) are crucial for sustainable development of urban centres and indeed entire countries. MSWMS deal with municipal solid waste from its generation at the source until its final disposal, including all the operations in between.

Collection and transportation of solid waste often accounts for a substantial percentage of the total waste management budget (including labour costs). The figure can reach over 70%, depending on geographical location and fuel price (Dogan and Duleyman, 2003; Ghose et al., 2006). Fuel consumption plays a dominant role in the costs of MSWMS. The vehicles can emit significant levels of undesirable atmospheric pollutant emissions, which include carbon dioxide (CO_2) and nitrogen oxide (NO_x), both of which are of major concern due to their contribution to the greenhouse effect and to acid rain. Reducing pollutant outputs through fuel economy therefore yields both environmental and financial benefits.

MSWMS provide a public service. Therefore, return on investment and profit margins are not major priorities. However, because waste management is a high-cost activity, it is necessary to justify the investment in terms of environmental, technological and economic feasibility. It is important that the required level of efficiency is achieved. Hence, optimisation of waste management is an issue that requires attention, particularly in the management of routing networks for waste collection and transportation.

Various optimisation models applied to different MSWMS can be found in the literature. Several studies have optimised particular (non-routing) operations related to waste management. Magrinho and Semiao (2007, 2008, in press) have studied the effects of both the screening process and moisture content on recycling rates. They also explored the possibility of increasing recycling rates for packaging materials while still keeping open the option of incinerating residual waste. Authors such as Baetz (1990) and Bhat (1996) have proposed the idea of adapting simulation modelling for optimal solid waste management planning. Others, such as Clark and Gillean (1974), have used analytical approaches to achieve the same goal.

Several authors have investigated route optimisation. Cordeau et al. (2002) and Simonetto and Borenstein (2007) used operational

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research methodologies to develop computer tools for vehicle routing optimisation. Morrissey and Browne (2004) reviewed the first models that dealt with specific aspects of route optimisation as applied to waste collection and transportation. They highlighted the vehicle routing system proposed by Truitt et al. (1969), and the transfer station siting study conducted by Esmaili (1972). Bodin et al. (1989), Tung and Pinnoi (2000) and Angelleli and Speranza (2002) performed optimisation of vehicle routing for waste collection using operational research methodologies. Badran and El-Haggar (2006) used operational research to develop a computer system based on a combination of quantitative techniques, such as simulation of discrete events, and heuristics for vehicle allocation. Everett and Riley (1997, 1998a,b) presented a model to calculate time taken during waste collection. It operated on the basis of total distance travelled and also took into account stoppage times. Their work led to several economic analyses. Sonesson (2000) extended the aforementioned research and also took into consideration the energy and fuel consumed during haulage and waste compaction. It is now widely accepted in this field that effective decision making requires the implementation of vehicle routing techniques.

Since routing models make extensive use of spatial data it is possible to take advantage of new technologies such as geographic information systems (GIS). GIS is able to provide effective handling, display and manipulation of both geographic and spatial information, as reported by Bodin and Golden (1981), Keenan (1998) and Armstrong and Khan (2004). In related work, Ghose et al. (2006) proposed a model for MSW collection that includes distribution of collection bins, load balancing of vehicles and generation of optimal routing based on GIS. The generation of route heuristics using GIS was performed by Viana (2006), focusing on the vehicle routing problem (VRP) applied to the optimisation of solid waste collection systems. To solve the VRP, a model based on the *ArcGIS* software and its *Network Analyst* extension was developed by the author, running on the Clarke and Wright savings heuristic with the two-optimal improvement heuristic and the genetic algorithm. GIS object classes were used to model the transportation networks. Supporting their study on GIS tools for road transport, Ericsson et al. (2006) proposed a model to estimate possible fuel savings and reductions in carbon dioxide emissions. Route optimisation was considered to mean lowering fuel consumption, rather than reducing time taking or distance travelled. Optimisation metrics were calculated using experimental fuel consumption values recorded from specific segments of the road network. Furthermore, the supplementary effect of real-time information about traffic disturbance events was also taken into account. More recently, Salhofer et al. (2007) proposed an evaluation of the environmental effects produced by complex waste management systems, where their work applied a life cycle based approach. For each selected product and waste stream, a life cycle analysis was performed with an emphasis on waste transport and related vehicle emissions. They considered different collection schemes, distances to treatment or disposal sites, means of transportation, and vehicle loads.

As summarised above, two-dimensional travel distance is the most widely used parameter for assessing the optimal routing for vehicles that collect and transport waste. Some additional constraints, such as speed, lifting of collection bins, waste compaction or traffic have also been taken into account. However, engine performance and efficiency are also influenced by a third spatial dimension that quantifies road slope, resulting in a variation of the engine power requirement and, thus, yielding different fuel consumption and vehicle emissions. Therefore, it would be advantageous to address road slope when determining the fuel consumption of trucks that collect and transport MSW. Such an approach is innovative and would provide the system an additional degree of freedom, the vertical direction, which would generate a more realistic cost function that takes into account both fuel consumption and associated emissions.

In the present work, we propose a GIS-based model that takes into account the relief of the terrain to calculate fuel consumption of vehicles that collect and transport MSW. Based on this model, it is possible to establish an optimal route for waste collection and transportation. The optimal route is defined as the one that minimises fuel consumption, which does not necessarily correspond to the shortest travelled distance. Indeed, depending on the slopes of the roads, it is possible for a longer route to become optimal in terms of fuel consumption. Such a model can be used as a decision support tool to improve the efficiency of waste management systems and thereby reduce the cost of waste collection and transfer to disposal sites. Although not considered in this paper, constraints such as speed, truck loading, the time taken to lift collection bins, waste compacting activities and traffic can also be incorporated into the present model. All experimental data used in this work to calculate fuel consumption of trucks transporting MSW was taken from the literature.

2. Description of the study area and existing waste management systems

The MSW treatment system in Cape Verde was selected as a case study. 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 10 islands, distributed as shown in Fig. 1. The population of less than half a million is spread over 9 islands. The largest and most populated island is Santiago, where the capital Praia is located, as depicted in detail in Fig. 1. Presently, about 55% of the total population of Cape Verde lives on the island of Santiago, with almost 25% of all inhabitants living in the capital. It is expected that, by 2020, the population of Santiago will account for 58% of the total, while Praia will account for 30%. In recent decades there has been an average annual population growth of 2.4% (INE, 2007), primarily driven by better work opportunities. Cape Verde is consequently a developing country that is experiencing good and sustained economic growth.

The city of Praia consists of several zones that are naturally separated by valleys. Santiago Island is similar in terms of the variability of the relief. The highest point of the island is Pico d'Antonia, at 1394 m above sea level, in the central part of the island.

A great challenge for Cape Verde is the establishment of an integrated and reliable MSWMS that guarantees proper treatment and disposal of waste. Amounts of generated wastes have been increasing dramatically as a result of urban pressure, demographic growth, tourism and other economic activities. Despite efforts at both state government and municipal levels (see Ministério de Agricultura e Pescas, 2002; Ministério da Economia, Crescimento e Competividade, 2003; Ministério do Ambiente, Agricultura e Pescas, 2004), urban development planning remains inadequate. The continued rural exodus and inter-island migration is not controlled. Existing waste management is still very basic and is characterised by an inefficient collection system. The collected waste is disposed in uncontrolled open landfill sites with subsequent *in loco* burning for volume reduction. There is no material or energy recovery. This results in a negative impact to the environment and public health and also negative effects on tourism. The collection and transportation system of Santiago Island with its six municipalities is divided into two regions: the capital Praia region, including its urban and rural areas, and the remaining zones of Santiago. Each municipality is responsible for waste collection and transportation to a landfill on its own territory, which constitutes the final and only treatment method for the collected waste.

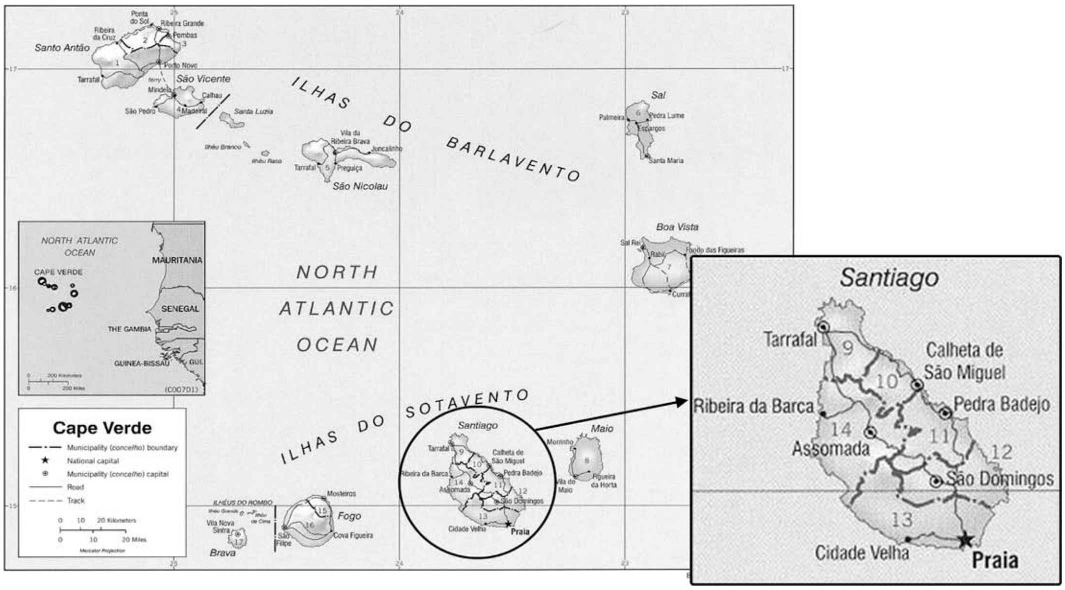

Fig. 1. Location map of Cape Verde. Detailed map of the island of Santiago and its municipalities, including the capital Praia.

2.1. Waste collection and transport in the Praia region

In the Praia region there is no selective collection of MSW. However, industries and traders, particularly wholesalers and retailers, handle their own waste collection and transport their waste directly to the landfill sites. All of Praia's waste (residential and commercial/industrial, and from both urban and rural areas) is disposed of in the São Martinho landfill, located some 4 km from the centre of Praia. It has been in service for 15 years and does not have any sanitary installations.

In the urban areas of Praia, waste is collected at returnable bins spread out through the entire city. The bins are emptied into compaction vehicles. By contrast, the rural areas feature a small number of community loading points. Each loading point often features a large open-topped container (or skip), which is collected by a hydraulic lever vehicle (the skipper) and replaced by an empty container. The actual capacity of the containers and collection vehicle fleet of the Praia region is presented in Table 1.

Waste is collected 6 days per week in the rural areas of Praia and 7 days per week in the urban areas. The skips are collected and emptied twice a week.

The street and road network of Praia is well built, and is comparable to European standards in terms of quality and durability. The roads are wide enough to be used by the waste collection vehicles without any problems. However, in the city centre, difficulties arise in certain areas because of old, narrow streets. In these areas, waste is collected through the use of skips located at the perimeters of the restricted zones.

2.2. Waste collection and transport in Santiago's other municipalities

Similar to the situation in the Praia region, there is no waste separation before collection in the other municipalities of Santiago Island. The available collection equipment can be characterised as a combination of 1.1 m^3 returnable metallic bins and 4 and 8 m^3 open-topped containers, the skips. Additionally, in the centres of more populated areas, such as Tarrafal, Assomada or Santa Cruz/Pedra Badejo (see Fig. 1), small plastic bins with capacities ranging from 50 to 800 l can also be found. In some parts of the island the waste is still collected by trailers, which are towed by tractors.

Unlike the Praia region, streets and roads in the remaining part of Santiago Island are not well built. Moreover, it should be noted that Santiago is a very mountainous island that therefore has many steep roads and streets. Waste is collected from returnable bins on a near-daily basis. However, collecting and emptying the large containers or trailers only takes place sporadically.

All collected waste is deposited in open uncontrolled landfill sites, where no further treatment takes place. The only exception is the municipality of Tarrafal, where a controlled landfill site has been recently built.

There is a project in progress for the thermal treatment of MSW by incineration. It is expected that the plant's substantial capacity will allow for the treatment of all waste collected from all the municipalities of Santiago Island, as well as its pre-treatment at intermediate transfer stations, a scenario which was taken into consideration in the present study. The transfer stations locations were chosen according to the demographic density of Santiago.

Table 1
The present capacity of the collection and transportation vehicle fleet at Praia region

Container type	No.	Unit capacity (m^3)	Total capacity (m^3)	Vehicle type	No.	Unit capacity (m^3)	Uncompacted waste capacity (m^3)	Total capacity (m^3)
Returnable bin	448	1.1	492.8	Compacting	7	12	30	210
	140	0.8	112.0					
Skip	50	8.0	400.0	Skipper	6	8	8	48
	40	4.0	160.0					
Total			1164.8					258

The most populated centres, and hence those that generate the largest amounts of MSW, are Tarrafal, Assomada and Santa Cruz, which are the ones more appropriated for such locations.

3. Methodology

This paper proposes a model whereby GIS is used to determine an optimal routing network that minimises fuel consumption and associated emissions for transporting MSW from a network of collection points to a thermal treatment plant. The model was developed to inform and optimise collection plans for the capital of Cape Verde, Praia. The work is also applicable to the transport of waste from the other municipalities of Santiago Island to an incineration plant located at Praia.

This work comprises three phases: phase 1 creates a 3D road network by means of the *ArcGIS 3D Analyst* extension; phase 2 calculates segment-wise fuel consumption along the entire road network; and phase 3 performs the optimisation of MSW collection for minimum fuel consumption by applying the *ArcGIS Network Analyst* extension.

A network is a system of interconnected elements. It can be visualised as a series of lines connecting points, such as roads connecting cities, or streets connected to one other at intersections. The *ArcGIS Network Analyst* (NA) extension can generate a network dataset (NDS) and perform analysis on it. Networks used by NA are stored as a NDS that is created from the feature source or sources in the network. Using the network attributes, it is possible to model impedances, restrictions and hierarchy. Network attributes are properties of the network elements that control local traversability. Examples of such attributes are the time to travel a given road length, the fuel consumption for a given road length, the nature of vehicle-specific restrictions for certain streets, the speed limit, and the locations of one-way streets. Certain attributes, such as travelled distance or fuel consumption, are used for measuring and modelling impedances. Network analysis often involves the minimisation of a cost (the impedance) during the calculation of a path (the optimal route). Common examples include finding the fastest route (minimising travel time) or the shortest route (minimising distance). Fuel consumption associated with 3D travelled distance is also a cost attribute of the network dataset that can be minimised. The addition of 3D data allows for a closer representation of reality.

For each phase, a separate module was developed using Visual Basic for applications (VBA) and *ArcObjects*. The resulting modules share information stored in a spatial database (SDB) created in the GIS environment. The structure of the developed model with its modules and the SDB is shown in Fig. 2.

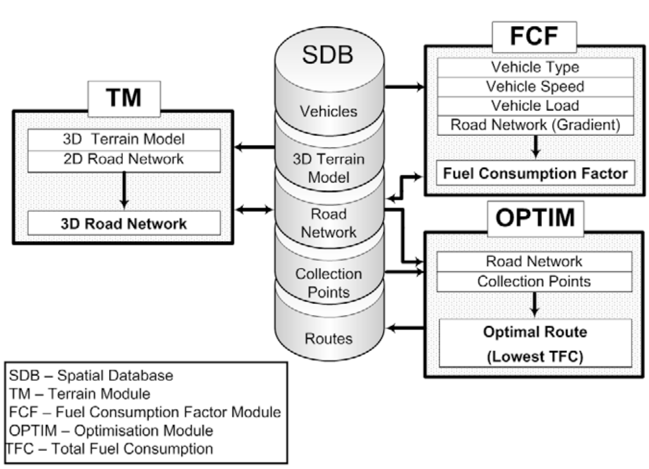

Fig. 2. Structure of the developed model showing its component modules and the spatial database.

3.1. Phase 1: 3D model of the terrain and representation of the road network

GIS technology has significant advantages in modelling urban networks. These are well documented in the literature, e.g., Santos and Rodrigues (2003), Tarantilis et al. (2004), Armstrong and Khan (2004), Ghose et al. (2006), Viana (2006), Ericsson et al. (2006), and Salhofer et al. (2007).

The first phase of the experiment required the use of GIS tools to build a SDB that stored data on the Cape Verde transport network. The SDB contained detailed digitised spatial road network information stored in the form of appropriate geographical objects (polylines, nodes, arcs, etc.). The nodes are the geographical point objects that define the beginning or the end of each network polyline. Each polyline is an array of points whose spatial distribution defines the geographical extent of any given road.

In order to account for the effect of terrain elevation, 3D models of Santiago Island and of Praia city were developed by the authors based on available 2D digitised maps provided as CAD files by the municipality of Praia. The 3D models were generated in the form of polylines based on contours that reflected terrain relief through the introduction of an additional coordinate, the elevation. To complete the 3D road network, the central lines of the 2D road networks were assigned an additional degree of freedom. Finally, the 2D maps were fitted to the terrain models in order to create a realistic model. In this way, each digital road segment reflected its actual physical characteristics in 3D space.

The 3D digital model and the road network for the city of Praia are shown in Fig. 3. As it can be seen, the previously reported irregularities of the city of Praia's terrain are obvious. The terrain in Praia, together with the high mountains in Santiago, reinforces the importance of road network gradients in calculating optimised fuel consumption for a waste collection fleet. This research makes it possible to generate meaningful digital networks that allow for the calculation of all inclinations of each road segment. In turn, this allows fuel consumption to be determined for both directions, as discussed in the following section.

3.2. Phase 2: calculation of fuel consumption (FC)

Fuel consumption during waste collection and transportation is influenced by the travelled distance and by the actual operating conditions of a given vehicle. In order to evaluate these effects, the method proposed in COPERT (Ntziachristos and Samaras, 2000) was used. COPERT is a computer program that calculates road vehicle emissions. COPERT also includes a framework for estimating fuel consumption. Besides considering specific vehicle parameters, COPERT also takes into account different driving conditions such as types of the driving situation, vehicle load and road gradient.

In the present study, the authors used the data available in COPERT for the category of diesel heavy duty vehicles (from 7.5 to 16 tonnes) and the EURO III legislation class (European Commission, 1999).

The basic fuel consumption as a function only of speed, FCS (g/km), is expressed for the considered vehicle category by the following equation:

$$\mathrm{FCS} = 1068.4V^{-0.4905} \tag{1}$$

Driving situation, classified as urban, rural or highway driving, can be represented by different mean driving speeds V (km/h), to account for variations in driving performance.

Furthermore, for heavy duty vehicles it is necessary to account for the effect of both vehicle load and road gradient. To evaluate the specific fuel consumption, fc (g/km), corrections are applied

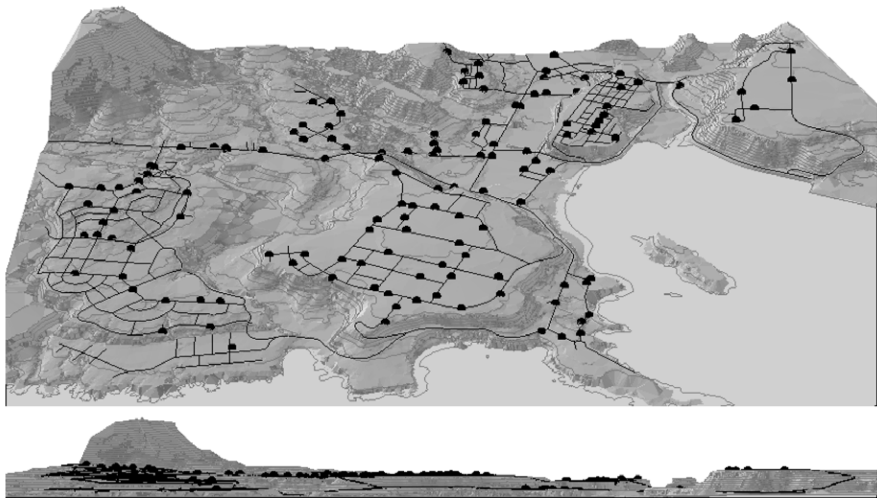

Fig. 3. A 3D digital model of Praia city showing its road network and MSW collection points.

to the FCS as expressed by Eq. (2), where LCF represents the dimensionless load correction factor and GrCF the dimensionless gradient correction factor

$$\mathrm{fc} = \mathrm{FCS} \times \mathrm{LCF} \times \mathrm{GrCF} \tag{2}$$

3.2.1. Effect of vehicle load

For any given road pattern, the vehicle engine operates under different loads as MSW is collected and loaded into the vehicle. The lower the vehicle weight, the lesser the load demanded from the engine, and vice versa. As a result, fuel consumption depends on vehicle weight. According to COPERT, to compensate for loads different from 50%, which is the reference value implicitly contained in Eq. (1), the consumption factor for heavy duty vehicles has to be corrected by the following equation:

$$\mathrm{LCF} = 1 + 0.36\frac{(\mathrm{LP} - 50)}{100} \tag{3}$$

In the previous equation, LP expresses the actual load as a percentage of maximum. For the sake of clarity, it should be stated that although LCF can be varied, it is not a dynamic factor since it remains constant for each collection route.

3.2.2. Effect of road gradient

The road gradient increases (when positive), or decreases (when negative) the resistance of the vehicle to traction. Therefore, the power required from the engine during driving is the key factor that determines vehicle fuel consumption. Because of their larger masses, the gradient effect is considerably greater in the case of heavy duty vehicles than for any other category. For each vehicle weight and gradient class, the gradient correction factor can be calculated as a polynomial function of the mean speed of the vehicle, as expressed by Eq. (4), where p is the degree of the polynomial function and A_0 and A_j are the function coefficients

$$\mathrm{GrCF} = A_0 + \sum_{j=1}^{p} A_j V^j \tag{4}$$

The data generated by the previous equation are valid for road slopes between −6% and +6%. The results were fitted to an exponential function so that a broader range of road slopes (−15% to +15%) could be considered. This is expressed by Eq. (5), where x represents the road slope percentage

$$\mathrm{GrCF} = 0.41\mathrm{e}^{0.18x} \tag{5}$$

Fig. 4 illustrates the experimental data that was derived from the empirical correlation expressed by Eq. (4) and the fitted exponential function.

3.2.3. Assigning FC values to each arc on the 3D road network

The 3D networks constructed as described earlier consisted of an array of arcs (geographical polyline objects) connected by nodes (the beginning and the end of the arc). Each arc is an array of vertices and segments. Vertices are defined as geographical points where the road changes direction or gradient. Segments are the straight lines that connect two adjacent vertices. In the 3D model used for this research, the length of each road segment depends on road gradient and has a specific fc associated with it. Any change in the road gradient requires a new road segment with a different fc. In this manner, the 3D route network model accounts for road inclination in the calculation of fuel consumption.

Fuel consumption for a given distance of travel is calculated for both directions (uphill and downhill). The fuel consumption at each arc FC_k is given by

$$\mathrm{FC}_k = \sum_{i=1}^{n} (\mathrm{Lseg}_i \cdot \mathrm{fc}_i) \tag{6}$$

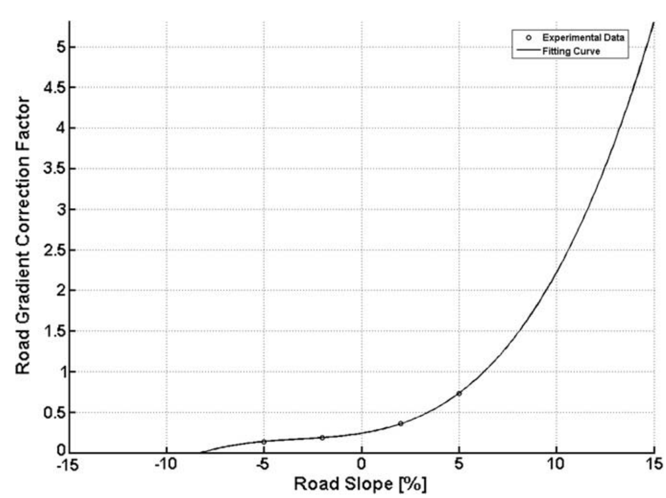

Fig. 4. Experimental data used for the road gradient correction factor, Eq. (4), and the fitted exponential function.

where $Lseg_i$ is the 3D length of the ith segment (km), fc_i is the corresponding fuel consumption of the segment i, and n is the number of segments included in the kth arc.

The fuel consumption value for each kth arc, FC_k, is stored in the SDB to be used later during the route solver procedure that determines the route that has the lowest fuel consumption.

3.3. Optimisation of vehicle routing for waste collection and transportation

The efficiency of a route management system can be measured in terms of its capacity to generate appropriately optimised routes. For a system that manages MSW collection and transportation, this requires that an optimal sequence of waste collection points be generated for a given collection vehicle such that all points are visited and the total fuel consumption (TFC) is minimal. For the optimal path, the minimum TFC is defined as the route that has the lowest fuel consumption among all possible routes that would still cover every collection point. The total fuel consumption for a given route (a defined sequence of arcs), TFC (g), is expressed by Eq. (7) as a function of the fuel consumption at each arc FC_k as previously defined by Eq. (6)

$$\mathrm{TFC} = \min\left(\sum_{k=1}^{m} \mathrm{FC}_k\right) \tag{7}$$

where m is the number of arcs included in a route.

For route optimisation, the model uses *ESRI's ArcGIS*, *ArcInfo* and *Network Analyst* extension software to identify the minimum defined impedance path through a network.

The complexity of the Santiago Island network problem is quite different from that of Praia. Accordingly, different approaches are required. For the Santiago Island network, the research used the Node Routing Problem solver, a well established procedure which is appropriate for situations in which the points (municipalities and incineration plant) are located at the nodes (vertices or road intersections). By contrast, the Arc Routing Problem solver, was used for Praia because the points to be visited (collection locations) were located along the arcs.

Using the aforementioned GIS applications, a Router Solver tool (the optimisation module) was developed by the authors to perform the calculations and to facilitate input and output data aggregation. Within the GIS environment, the vehicle router finds the optimal sequence of destinations by computing the minimum impedances between clusters of collection points and the final destination using the *Network Analyst* extension module. The resulting route is saved in a route-system file structure and can be viewed using the route display commands.

In both cases, when the Route Solver procedure is executed, the routes are optimised for the cost function associated with the lowest fuel consumption or the shortest distance. For each of these optimised parameters (e.g., the 3D shortest distance), the remaining parameters (the 2D distance and the fuel consumptions, 2D and 3D, for that route) are estimated to allow for subsequent comparisons.

4. Results and discussion

At present there is neither an incineration plant nor a transfer station at Santiago. The collected waste is directly deposited in local landfills. Accordingly, the incineration plant location used in this work is the one planned by the Cape Verdean government,

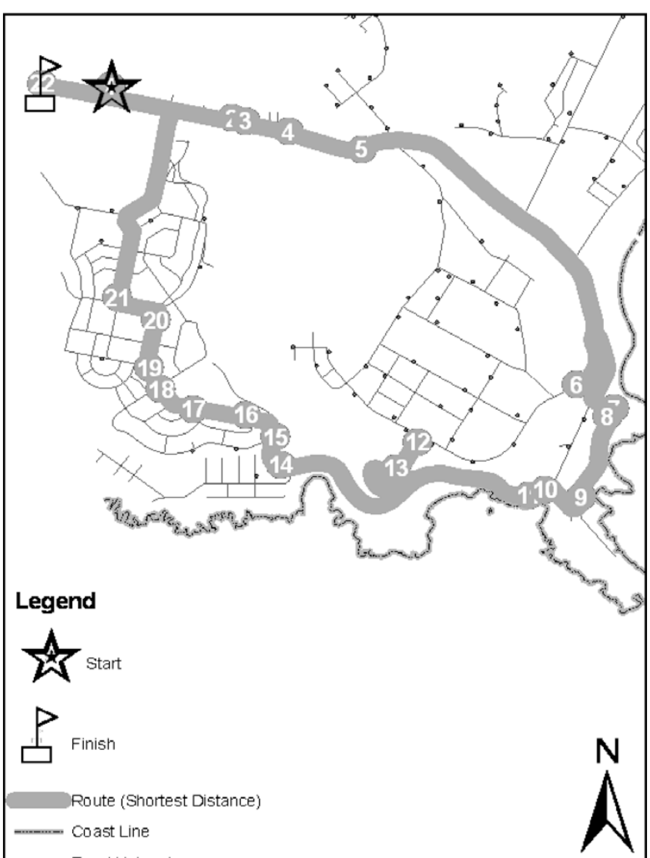

Fig. 5. The MSW collection vehicle route for Praia city, optimised for the shortest 3D distance.

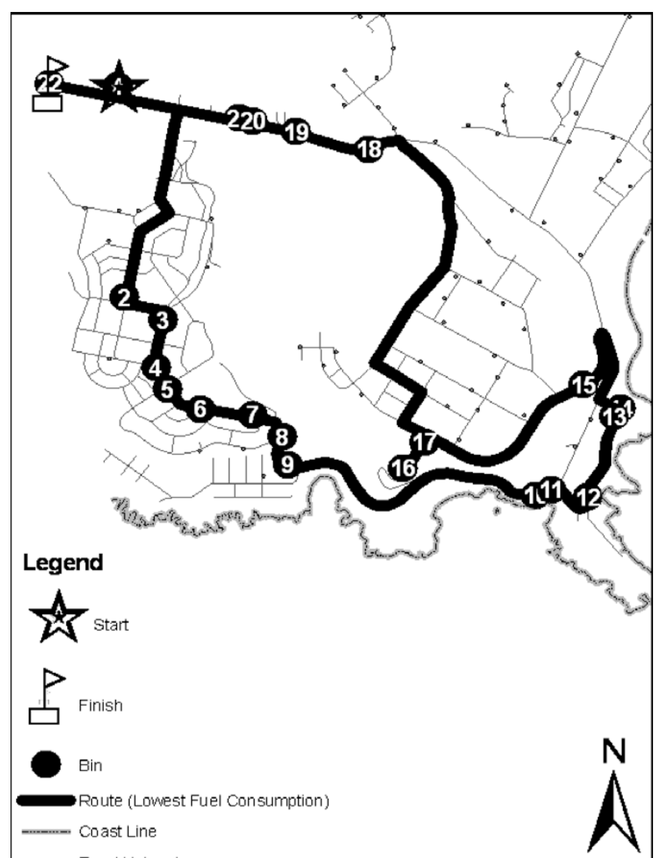

Fig. 6. The MSW collection vehicle route for Praia city optimised in 3D for the lowest fuel consumption.

as mentioned in Section 2. It is assumed that waste would be delivered from all six municipalities, in accordance with the current government plan. Under these assumptions, the previously outlined model is applied to study and analyse two different waste collection and transportation schemes for Santiago Island. The work quantifies the effect of road gradient on fuel consumption:

(1) Waste collection from the city of Praia with direct transportation to the incineration plant, known as kerbside collection.
(2) Waste transportation from Santiago municipalities (transfer stations) to the incineration plant, an origin-destination trip.

4.1. Praia waste collection system

In the city of Praia, only returnable collection bins with capacities of 1.1 m^3 are considered in the calculations. Some of the collection points comprise more than one bin. The 12 t compaction truck starts its trip at the garage, collects the waste from the returnable bins at predefined locations and moves towards the final destination, making a closed loop circuit. The goal is to identify the most economical route to collect MSW from 20 predefined locations. An average vehicle speed of 20 km/h is assumed. It should be noted that the maximum, and hence the average, velocity of the truck depends on the road grade. In fact, on a steep uphill, the truck might not reach 20 km/h, whereas, on a downhill run, speeds in excess of 20 km/h may occur. This dynamic truck motion could potentially be incorporated into the current model in the future. Furthermore, both truck idling and loading operations are considered not to consume fuel. In spite of these model limitations, the problem remains tractable since one is comparing routes in a closed loop circuit with the same loading operations. Moreover, the primary purpose is to show that the cost function that minimises fuel consumption in a three-dimensional frame is more appropriate than the equivalent function that minimises distance travelled. The total impedances for the cluster are calculated by the model through the optimal path and then displayed as a route.

The route computed for the shortest 3D distance required to collect MSW from the aforementioned 20 collection points is shown in Fig. 5. The route optimised for the lowest fuel consumption to collect MSW from the same collection points is presented in Fig. 6. Comparing the two optimised routes it is possible to observe that the direction of travel and sequence of visited collection points is quite different. When using the shortest 3D distance as the cost function, the direction taken by the truck (clockwise or counterclockwise) makes no difference to the solution because it has no bearing on total distance travelled. Furthermore, the model is insensitive to road gradients. That is why the vehicle approaches its final destination climbing the hill from the collection point 14 up to point 21. On the other hand, when optimising the 3D route to minimise fuel consumption, a strong preference is given to downhill routes that minimise vehicle elevation gain over the total trip (see Fig. 5). This is also obvious in Fig. 7, which shows the terrain elevation of the truck route and the corresponding consumed fuel as a function of the actual 3D distance travelled. From the previous discussion and from Figs. 5–7, it is clear that the optimisation avoids steep ascents, and chooses different routes that minimise fuel consumption, even if those routes end up resulting in a greater total travel distance.

Table 2 shows numerical results for the optimised waste collection routes displayed in Figs. 5–7. Comparing the route optimised for the shortest 3D distance with that optimised for lowest fuel consumption, the observed differences may not seem significant.

Table 2
The results for the optimised waste collection routes at Praia

Calculated parameters	Optimisation criterion	
	Distance 3D	Fuel consumption 3D
Distance 2D (m)	8246	8395
Distance 3D (m)	8254	8401
Ascending 3D distance (m)	4012	3652
Descending 3D distance (m)	3326	3689
Horizontal distance (m)	916	1060
Fuel consumption 2D (g)	2266	2307
Fuel consumption 3D (g)	2920	2686
Difference in distance travelled (3D–2D) (m)	8	6
Difference in fuel consumption (3D–2D) (g)	654	379

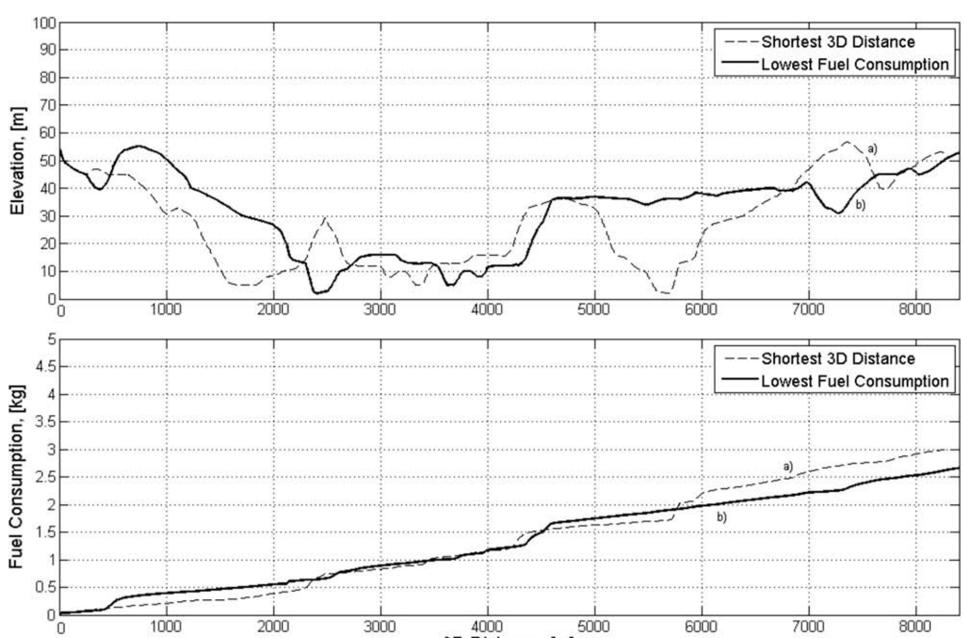

Fig. 7. Elevation and fuel consumption profiles along the MSW collection route at Praia city. (a) Route optimised for the shortest 3D distance. (b) Route optimised for the lowest fuel consumption.

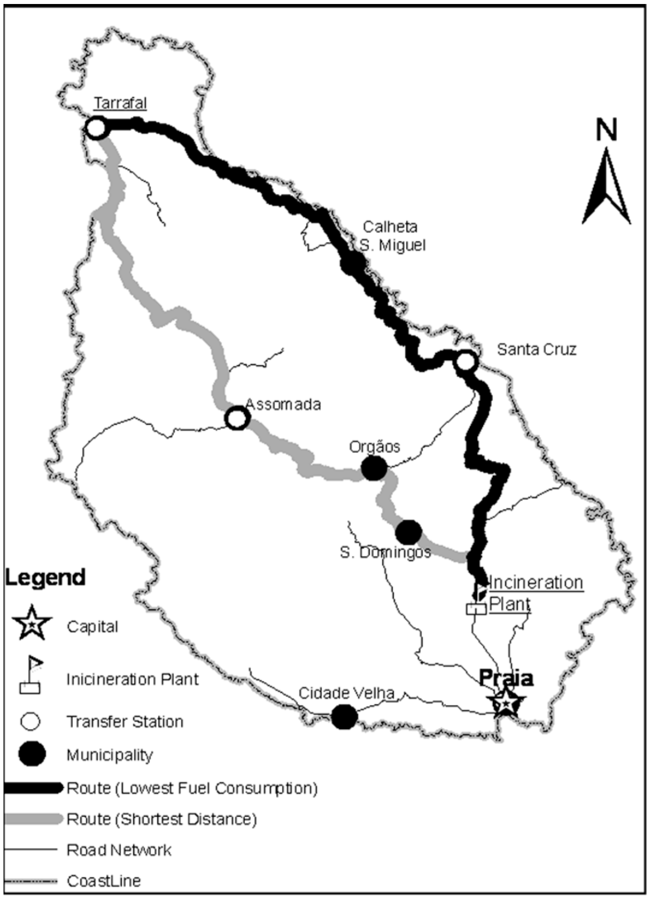

Fig. 8. The spatial distribution of the municipalities, hypothetical transfer stations and the location of the incineration plant. Overlaid are the waste transportation routes, optimised using 3D GIS firstly for the shortest distance, and secondly for the lowest fuel consumption.

The change is about 1.8% in terms of 2D travel distance (8246–8395 m); in terms of 3D travel distance, the change is similarly marginal (8254–8401 m). However, the 3D fuel consumption parameter shows a fuel saving of 8% (from 2920 to 2686 g). Two factors explain this value: the ascending distance travelled was reduced by approximately 9% (from 4012 to 3652 m) while the horizontal distance travelled changed by 16% (from 916 to 1060 m).

Although the differences in terms of 2D and 3D distances are quite small for a given optimisation criterion (8 and 6 m), the differences in fuel consumption are considerable (some 29% and 16%, corresponding to 654 and 379 g, respectively). Importantly, the 3D model reflects differences in engine power output during the uphill and downhill travel. It should be stressed that the results show that the lowest fuel consumption (2686 g) is obtained when the truck travels the longest distance (8401 m).

These results support the need to account for terrain variability in calculating the fuel consumption of waste collection vehicles.

4.2. Santiago waste transportation system

The major Santiago roads and transfer points, including the location of the destination, were chosen from available spatial data, as depicted in Fig. 8. The vehicles used for waste transportation on such long distances are skippers, which lift only large dimension containers and carry only one container at a time. The average vehicle speed is assumed to be 30 km/h. The case of waste transportation from the transfer station of Tarrafal to the incineration plant is presented. As before, the maximum, and hence the average, truck velocity depends on the road grade. The same logic used to justify the average velocity of 20 km/h in Praia also applies here.

As demonstrated in Fig. 8, different routes are generated according to the optimisation criteria applied. While the route passing the central hilly part of the island is chosen by the shortest distance model, a route optimised for minimum fuel consumption follows the eastern coastline, which features much gentler gradi-

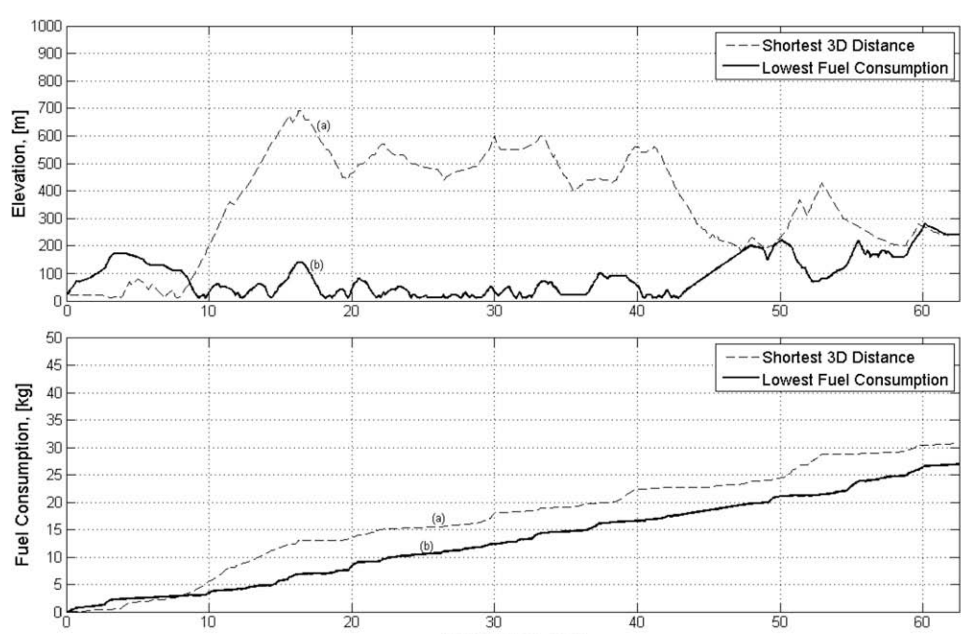

Fig. 9. Elevation and fuel consumption profiles along the MSW transportation route in Santiago Island. (a) Route optimised for the shortest 3D distance. (b) Route optimised for the lowest fuel consumption.

Table 3
The results for the optimised waste transportation routes from Tarrafal transfer station to the incineration plant

Calculated parameters	Optimisation criterion	
	Distance 3D	Fuel consumption 3D
Distance 2D (m)	61,942	62,408
Distance 3D (m)	62,102	62,528
Ascending 3D distance (m)	25,422	24,843
Descending 3D distance (m)	24,945	20,570
Horizontal distance (m)	11,735	17,115
Fuel consumption 2D (g)	17,021	17,149
Fuel consumption 3D (g)	30,670	26,930
Difference in distance travelled (3D–2D) (m)	160	120
Difference in fuel consumption (3D–2D) (g)	13,649	9781

ents. These fuel consumption savings associated with moderate elevation changes are evident in Fig. 9, which shows the terrain elevation of the skipper route and the corresponding consumed fuel as a function of the actual 3D travelled distance.

The numerical results for this case are presented in Table 3. These results confirm the importance of taking into account the relief of the terrain. When switching from the 2D model to the 3D model, the fuel consumption increased by 80% (from 17,021 to 30,670 g) under shortest 3D distance criterion, and by 57% (from 17,149 to 26,930 g) under the lowest fuel consumption criterion. Additionally, 3D fuel consumption was reduced by 12% (from 30,670 to 26,930 g) when the optimisation criterion was switched from the shortest 3D distance to the lowest 3D fuel consumption. Again, although the distance travelled is slightly longer (from 62.1 to 62.5 km in the 3D calculations), the total fuel consumption decreases as a consequence of the model selecting roads with lower gradients. As previously explained, this is to be expected since there were two cumulative gains: one from the ascending distance travelled of 2.3% (from 25,422 to 24,843 m) and another of 46% (from 11,735 to 17,115 m) from the horizontal distance travelled.

From the previous analysis it can be concluded that both terrain elevation and route optimisation through minimisation of fuel consumption are important factors for the management of waste collection and transportation vehicles.

5. Conclusions

The objective of this research was to develop a model to optimise the routing of MSW collection vehicles using the fuel consumption as a core criterion and taking into account local road gradients. Such a model was developed in the GIS environment using *ESRI's ArcGIS* 9.1 software and its extensions (*3D Analyst* and *Network Analyst*). The model was applied to two collection and transportation schemes to demonstrate its advantages over the use of both 2D models and the travelled distance as the cost function. The first study was MSW collection from the city of Praia in Cape Verde and the second considered waste transportation from the transfer stations of Santiago Island's municipalities to the incineration plant.

In the case of the city of Praia, considerable differences were observed in between 3D and 2D fuel consumption for a route that had been optimised under the same criteria (29% for the shortest 3D distance and 16% for the lowest fuel consumption). This is due to the different engine power output that is needed to travel uphill vs. downhill, a factor that is only taken into account when using the 3D model. Moreover, the 3D model for the lowest fuel consumption, when compared to that for shortest 3D distance, resulted in an 8% fuel saving even for a travelled distance that was 1.8% longer.

For the Santiago Island scenario, the optimal routes for the transportation of waste to the incineration plant reinforced the importance of 3D modelling to calculate fuel consumption. Regardless of the optimisation criterion used – the shortest distance or the lowest fuel consumption – the switch from the 2D model to the 3D model yielded fuel consumption increases of 80% and 57%, respectively. Moreover, a 12% fuel saving was obtained when shifting from the shortest 3D distance criterion to the lowest 3D fuel consumption optimiser.

The results of this study demonstrate the relevance of optimising MSW collection vehicle routing for minimum fuel consumption, rather than shortest distance or time. The work also recommends the use of 3D modelling, rather than 2D, particularly where significant road gradients exist.

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