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GIS-based approach for optimizing biowaste collection services in rural small sized municipalities

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ABSTRACT

Directive (EU) 2018/851 of the European Parliament and of the Council establishes the obligation for Member States to ensure, by 31 December 2023, that biowaste is separated and recycled at source or collected selectively. As this is a responsibility of the municipalities, studies to evaluate the best solutions and to ensure the rationality of the investments to be made to fulfill these objectives is of particular importance. Bearing in mind the new municipality's responsibility, this article aims to demonstrate the applicability of GIS in supporting planning and decision of a new service provided to the population. The solutions found must be economically sustainable and feasible for small size municipalities, especially for those with no formal biowaste management system implemented and with reduced resources. It is therefore proposed an approach to analyze vehicle route optimization for the selective collection and transportation of biowaste in markedly rural municipalities with a strong forestry component, equating solutions that allow their recovery, as well as the promotion of the management of forest spaces. The Network Analyst extension of the ArcGIS® software was used to answer questions related to travel time route optimization, optimal location selection and definition of service areas. The analysis performed allowed to identify and evaluate the main factors that minimize the costs associated with the undifferentiated and selective collection and transportation of biowaste in the study area (Oleiros-Amieira parish, Portugal). It was determined the need to distribute the service through 3 different routes, as well as optimizing the location of a biomass plant fed by forest remnants deposited in community containers spread across the study area. Developing simpler and cost-effective instruments for reducing waste transport costs for small forest owners and municipalities, such as the proposed one, is essential to ensure a successful implementation of Directive (EU) 2018/851.

Introduction

The production of waste, which is considered as any substance or object that a holder discards, intends to or is under the obligation to discard, is a consequence of the use of resources involved in the various socio-economic activities that characterize everyday life (Portuguese Ministry of Environment and Spatial Planning, 2011; Sulewski et al., 2021). Waste is originated in several stages of the socio-economic metabolism, from the moment the materials are extracted from nature until these materials and the products into which they are transformed are no longer useful to the consumer. In essence, waste generation exists because no production process is 100 % efficient and because a large part of what is produced has an end-of-life, becoming waste. However, with the emerging environmental concerns that derive from the high quantities of waste produced by humans, this is now seen by government decision-makers as a resource and not as an unwanted or unusable material, which is why there is currently a focus on its recovery and recycling (Moretti et al., 2020a; Schüch et al., 2017; Sulewski et al., 2021).

The Portuguese General Waste Management Scheme (Portuguese Presidency of the Council of Ministers, 2020), in accordance with the Council Directive 1999/31/EC (Council of the European Union, 1999), describes 'municipal waste' as waste from householders, as well as other waste that, by its nature or composition, is similar to waste from

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householders. Municipal waste has some characteristics that distinguish it from other wastes, such as origin, production volume, composition and management model. It is produced by a very large and dispersed number of producers, especially domestic consumers, which results in a challenging process for its management (Portuguese Environment Agency, 2020). This process, when inadequate, generates immediate impacts on the environment, population health and economy (Ait Errouhi et al., 2018; Geissdoerfer et al., 2017; Gruler et al., 2017; Meena et al., 2023; Sulewski et al., 2021).

In recent years, there has been an increase in the awareness for the separation of'domestic waste', preventing the waste that can be recycled from being sent to landfill and ensuring its use in the production of secondary raw materials that can replace extractive raw materials (European Environment Agency (EEA), 2020). However, especially in urban centers, organic waste is generally mixed with undifferentiated waste. 'Organic waste' or 'biowaste' consists of biodegradable waste from green spaces, kitchen housing, meals' and retail's supply units and similar waste from food processing (Höhn et al., 2014; Lavigne et al., 2021; Sulewski et al., 2021). It represents 34 % of the total municipal waste produced in the European Union (European Environment Agency (EEA), 2020). Recent studies have shown that the management of domestic organic waste collected separately and treated through composting or by anaerobic digestion has better environmental performance, when compared to incineration or landfill (Andersen et al., 2012; Boer et al., 2021; Colón et al., 2010; Edwards et al., 2015; Lovrak et al., 2020; Meena et al., 2023; Ranieri et al., 2018; Slorach et al., 2019; Sulewski et al., 2021). Although the anaerobic digestion cost/ton is not the lowest, this is the solution that presents the highest annual savings (Moretti et al., 2020b; Xu et al., 2019). In fact, when biowaste is collected selectively and properly routed for treatment and recovery, it can be taken full advantage of its environmental and economic potentials (European Parliament and Council, 2018; Pubule and Blumberga, 2014; Savini, 2019; Secretaria de Estado do Ambiente, 2020; Slavík et al., 2021). For the success of this new concept, it is essential that urban waste management, which comprises all operations related to collection, transport, storage, sorting, recovery and elimination, stands out for its effectiveness, efficiency and quality. The closure of the biowaste material cycle and the transition to a circular economy model will only be possible with policy instruments that fully, and in the long term, include not only minimizing the production of waste, but also its proper recycling and management (European Commission, 2020; Geissdoerfer et al., 2017).

Directive (EU) 2018/851 of the European Parliament and the Council (2018), amending Directive 2008/98/EC on waste, was approved on May 30th 2018 and transposed into the Portuguese legislation under the General Waste Management Scheme (Portuguese Presidency of the Council of Ministers, 2020). This revision introduced the obligation to implement networks for the selective collection of biowaste or to proceed with the separation and recycling at the biowaste origin, introducing the goal of reducing deposition in landfills. In order to achieve this end, Member States must ensure that, from 2030 onwards, landfills do not accept any waste that is suitable for recycling or recovery. In Portugal, the responsibility for this biowaste selective collection and recycling at source lies with municipalities and management entities that are responsible for the treatment and recovery of biowaste. Therefore, it is up to the municipalities to define the best way to manage them, either by themselves, or by hiring third parties. To do so, cost-effective and environmental impact criteria (such as transport pollutant emissions and costs) must be followed. To reach this end, it is important to study and evaluate the best solutions, as well as to ensure the rationality of investments. Derived from a careful analysis of the available options and the associated costs, several questions inherent to the process of collecting and transporting biowaste can arise, namely whether to adopt a door-to-door collection or to resort to community or home composting. When the collection of bio-waste has no economic potential and there is the need to opt for composting, it is essential to analyze vehicle collection routes, costs and composters' location (Portuguese Environment Agency, 2019).

In this context, it is also important to distinguish between the two types of biowaste that municipalities have to deal with: 'food waste' (waste from food preparation and consumption) and 'green waste' (waste from the cleaning of gardens and vegetable gardens, as well as agricultural and forest remnants). The first type of biowaste is responsible for unpleasant odors and requires a more complex management, while green waste degrades slowly and its management is easier. Taking these characteristics into account, the collection of green waste should be done separately from that of food waste. The collection of green waste can also be less frequent and its recovery can be done in decentralized composting units (Environmental Fund, 2021).

In this regard, a great difference between large and small urban environments can be found, since housing configuration dictates different solutions for the municipality's obligation. For a large city, domestic composting will be viable only in neighborhoods where houses with gardens are dominant. On the other hand, community composting can be adopted when dense housing units are located in the vicinity of public gardens, where larger composters can be placed and the reuse of biowaste as fertilizer for these green leisure spaces can be done under municipality management. For housing units where the predominant typology is apartments without green spaces, the solution of door-to-door collection will have to be maintained, along with what is already done with undifferentiated waste. This is the case of several Portuguese cities such as Maia, Oeiras, Cascais, and many other urban centers that are developing pilot projects for waste separation, simplifying the role of the citizens without increasing the costs of collection. In large urban centers, it will be feasible to set up a door-to-door and a green waste collection service at the citizens' request. For rural municipalities with a strong forest component, such as Oleiros municipality (Portugal), food waste is already naturally used by most of the population for animal feeding. However, the separation of biowaste at source is equally necessary, mainly by family nuclei that do not have animals or vegetable gardens. In these rural municipalities, it is worthwhile to separate the green waste originated from agricultural and forest remnants and cleaning of gardens and vegetable gardens, since they are usually deposited in undifferentiated waste containers or discarded by burning, causing a significant number of fires by negligence.

According to Sulewki et al. (2021), the cost of collecting urban waste it is expected to decrease when the population is properly instructed for waste separation, since it is assumed a lowering in the waste quantity by diversion of part of the biowaste for domestic composting. Consequently, the number of trips required for waste collection will be reduced. At the same time, the number of green waste burns is expected to decline by the offering of a municipal green waste collection service, which could even trigger the deployment of a biomass plant fed by this type of waste.

To address the challenge of biowaste management, several methods to find and support solutions for biowaste collection, transportation, disposal, storage, monitoring and transformation (production of chemicals and energy) have been studied using GIS, via spatial inventory and analysis. The use of GIS offers several benefits, such as improved decision-making due to enhanced waste management analysis and visualization of data. Many of the existing approaches combine spatial analysis with multi-criteria (Ait Errouhi et al., 2018; Dima et al., 2022; Slavík et al., 2021), p-graph (Kodba et al., 2023), optimization (Lavigne et al., 2021; Thiriet et al., 2020), statistical (Lovrak et al., 2020) or techno-economic (Matthew and Spataru, 2023) methods. Among these studies, it is possible to highline the use of GIS for biowaste resources inventory and distance calculation to support modeling and optimization (De Buck et al., 2022; Lavigne et al., 2023; Thiriet et al., 2020), to analyze the number and location of biowaste containers (Slavík et al., 2021), for biowaste collection and transportation optimization (Ferronato et al., 2020; Höhn et al., 2014; Kodba et al., 2023; Lavigne et al., 2021; Matthew and Spataru, 2023; Tampio et al., 2017; Thiriet et al., 2020; Zsigraiova et al., 2013), municipal landfill site selection (Ait Errouhi et al., 2018; Ouma et al., 2011; Şener et al., 2011; Sumathi et al., 2008), storage and biogas/biomass plant location (Chukwuma et al., 2021; Dima et al., 2022; Höhn et al., 2014; Valenti et al., 2018) and assessment of the spatial distribution of biofuel/biogas production potential (Lovrak et al., 2020; Sharma et al., 2017). However, studies that demonstrate the usefulness of GIS-based approaches to support decision in biowaste management for small-sized municipalities with limited resources, covering and integrating structural and daily services, were not found by the authors.

In view of the above, this article aims to present the application of a spatial decision support instrument to aid decision-makers responsible for rural small size municipalities that have no formal biowaste management strategy and face limited resources. It aims to boost the sustainable management of biowaste. This challenge is addressed by providing an accessible, simpler, low-cost and reliable tool for the analysis and selection of optimized waste and biowaste collection transportation services, as well as biowaste transformation plant location. For this purpose, a geographic information system (GIS) is used and its potential and applicability to optimize municipal daily cleaning services is explored.

The article is organized as follows: The Introduction presents a framework on the biowaste concept and characteristics, the challenges of its management and the use of GIS-based approaches for this purpose. The methodology proposed for biowaste collection and transportation optimization for rural small size municipalities using the ArcGIS's Network Analyst extension is presented in the Method and data section. In the Case study section, several pertinent and hypothetical scenarios are studied and discussed, validating the adoption of the approach for undifferentiated waste and biowaste collection transportation services in rural small sized municipalities. It was considered interesting to study solutions for the case of the largest parish of Oleiros municipality (Portugal), i.e., the parish of Oleiros-Amieira, since it brings together the rural and urban realities. Finally, the main findings and future work directions are presented in the Conclusions section.

Methods and data

This section presents the main phases of the methodology proposed by describing the operations performed when applying a GIS-based decision support instrument to optimize undifferentiated waste and biowaste collection, as well as transportation services in rural small sized municipalities. GIS-based instruments are recognized by several authors as a powerful approach for enhancing waste management (Chukwuma et al., 2021; De Buck et al., 2022; Kodba et al., 2023; Thiriet et al., 2020). The methodology includes the following phases: gathering, organization and treatment of the initial road network and waste vector and alphanumeric data (inputs); correction and validation of the road network; creation of the Network Dataset that supports the network analysis; execution of the networks analyses; visualization and evaluation of results (outputs).

The base cartography of road network can be obtained from free geodata portals, such as Geofabrik (Geofabrik, 2023) or, if available, directly from municipal services. The cartography must be worked to delimit the area of interest for the analysis and to check topology requirements. For the latter, the ArcGIS's Check Error Network tool is used for the identification and correction of topology errors. Since these data generally includes common and forest roads, only the sections through which the urban solid waste collection vehicle could travel must be selected, considering the dimensions of the available vehicles. At the same time, the attribute table of the obtained road network model is completed and filled with alphanumeric data that supports the network analyses. The minimum set of information required to perform the analyzes is presented in Table 1.

In addition to the road network information, other essential elements needed to perform the analyses, such as the administrative boundaries

Table 1
Road network alphanumeric data.

Field	Data type	Description
Oneway	Text	FT: "From-To", traffic movement according to line direction TF: "To-From", traffic movement opposite to line direction N: No traffic circulation B: Circulation in both directions
Lenght_km	Double	Road section length in km
Speed	Integer	Average traffic speed (km/h) Note: The average traffic speed is considered as a function of the road class. For the case study presented, the head of the cleaning service division, after consulting the three drivers of the municipality's urban solid waste collection service, reported the following average speeds according to road class (includes stopping time in each waste container): Arterial – 60 km/h Major collector – 40 km/h Minor collector – 30 km/h Access roads – 20 km/h
Minutes	Double	Travel time in minutes (calculated for each road section)
Street_name	Text	Street name. Helps generate itineraries. Note: A generic name can be given to road sections without toponymy assigned.
Road_class	Integer	1 – Roads where the maximum speed reached by the vehicle is 60 km/h 2 – Roads where the maximum speed reached by the vehicle is 40 km/h 3 – Roads where the maximum speed reached by the vehicle is 30 km/h 4 – Roads where the Maximum speed reached by the vehicle is 20 km/h
Elevation	Integer	F_Elev, T_Elev: Two elevation fields are considered to reflect circulation directions in the analysis (F - From-To and T – To-From) Ensures connectivity of uneven roads Lines 0–1 do not cross Lines 0–0 intersect at the junction point

(official geodata portals), waste collection vehicles number, capacity and departure and arrival location (municipal warehouses), waste containers' position and capacity (information provided by the municipality) and waste disposal locations (e.g., waste transfer station or biomass plant) are gathered and included in the GIS model. These data can be obtained from public authorities governing the analyzed area, as well as from national and regional entities with official and available georeferenced data.

Considering that biowaste collection transportation costs comprise operational costs, such as fuel and personal cost, and investment costs related to vehicle acquisition and maintenance (Lavigne et al., 2021), to perform the cost optimization network analysis, two cost attributes are considered: distance in kilometers and time in minutes. The first one is calculated using de ArcGIS® software and the second one is derived by dividing the travel distance by the driving speed (see Table 1). Finally, using the road network model, the routes for the collection and transportation of waste and biowaste oriented towards the specific needs of rural and small sized areas (number of waste containers (stops), number and loading capacity of waste collection vehicles and cleaning team shifts time) can be analyzed, in order to optimize service cost for various scenarios by reducing time spent in the route and distance travelled and, consequently, fuel consumption and pollutant emissions. The analysis is performed using the ArcGIS's Network Analyst extension functionalities: New Route, New Location-Allocation, New Closest Facility, New Service Area and New OD Cost Matrix (Bolstad, 2016; Esri, 2021; Fischer, 2006). By this way, the transport distances and time spent are estimated based in real road infrastructure distances and characteristics, improving the accuracy of results. Fig. 1 depicts the procedure

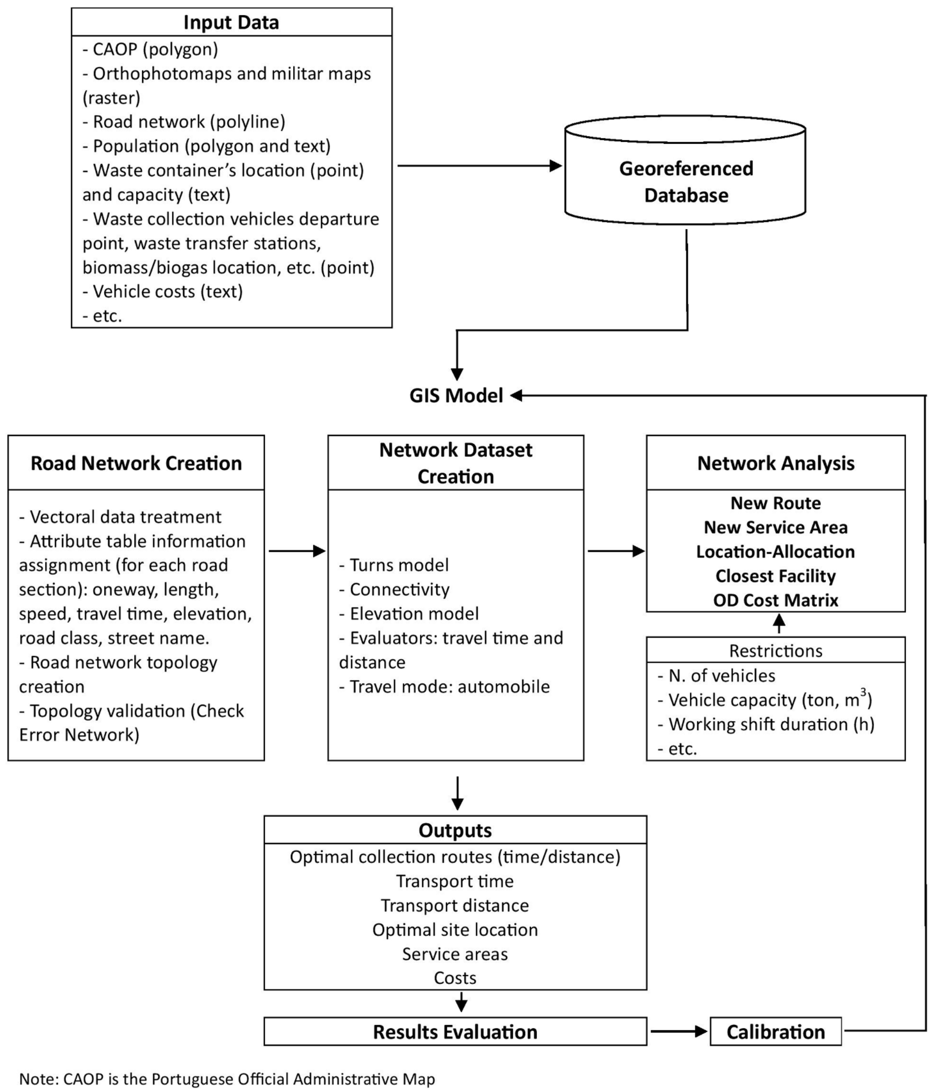

Fig. 1. Methodology for evaluating waste management scenarios.

described.

Examples of the methodology application to optimize a set of scenarios that can arise in rural and small sized municipalities that aim to optimize the management of undifferentiated waste and biowaste are presented in the section Case study.

Case study

Study area

The proposed methodology was applied to the largest parish of Oleiros municipality, which is named Oleiros-Amieira (Portugal). According to the provisional results of the 2021 census, this parish, with a territorial area of 143.64 km^2, has 2080 inhabitants and 895 households (Statistics Portugal, 2021). This parish was chosen because two types of reality for biowaste collection can be considered:

- Door-to-door collection of food waste that cannot be composted at home, either because of its characteristics (not all organic waste can be used in composting) or the housing typology (no private green spaces).

- Collection of green waste. This parish has the highest number of agricultural green waste burnings, according to data from the Portuguese Municipal Forest Technical Office (Portuguese Institute for the Conservation of Nature and Forests, 2022).

Thus, regardless of the domestic composting project that can be implemented to reduce the volume of biowaste by reuse at source, the remaining food waste and undifferentiated waste should be collected. As stated by Lavigne et al. (2021), this operation can take advantage of the current or optimized undifferentiated waste collection routes, without the need to create specific ones for the selective collection of biowaste. It is expected that, after raising the population awareness about domestic composting, weekly collection frequency can be reduced, since biodegradable waste that causes unpleasant odors will exist in smaller quantities.

In this sense, the methodology applied aims to analyze routes for the collection of municipal solid undifferentiated waste and biowaste, simulate cleaning transportation-based services and optimize biomass plant location for the Oleiros-Amieira parish. For this purpose, the road network model is prepared to perform optimized analyses for various scenarios, aiming to reduce distance travelled and time spent in the route and, consequently, fuel consumption and pollutant emissions.

Road network

The base cartography available in Oleiros municipality was used. This cartography includes the entire road network of the municipality, which was worked by delimiting the area of interest for the analysis, the Oleiros-Amieira parish (Fig. 2 a). Since the data included common and forest roads, only the sections through which the urban solid waste

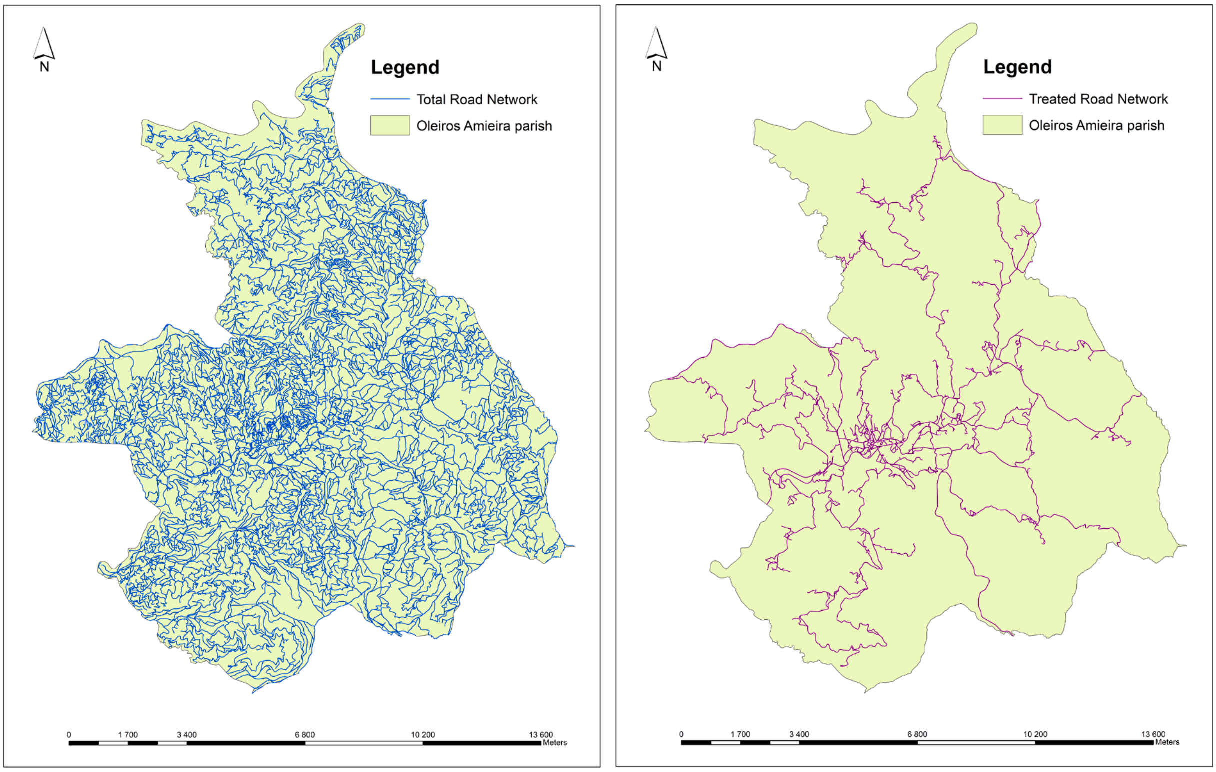

Fig. 2. Treatment of the road network: a) original network; b) network considered in the analysis.

collection vehicle could travel were selected. The operation of selecting the network according to the dimension of the collection vehicle resulted in a reduction of the road network length from 1569 km to 243 km (Fig. 2 b). The Clip tool applied to the road network and parish boundaries shapefiles originated several road cuts near the administrative limits. These situations were corrected by manually editing the shapefile, in order to ensure the continuity of the roads. To ensure connectivity in all existing intersections, the Planarize Lines tool was used, resulting in a road network model with 2643 road segments. Then, the attribute table of the obtained road network was completed and filled according to Table 1. The Oneway field was validated for all road sections of the road network, particularly at roundabouts and roads within villages, where circulation takes place in only one direction. Other fields were automatically filled in using the Calculate Geometry and Field Calculator tools, for example, the fields of length and time.

Thereafter, the identification and correction of topology errors was performed using the Check Error Network tool (280 errors). For that, a new Personal Geodatabase was created and, within it, a Feature Dataset. Since the road network was initially created in a shapefile, it was converted to a Feature Class and added to the Feature Dataset and, from this, a New Topology was created. The topology rules considered of interest for the correction of the road network topology were 'Must Not Have Dangles' and 'Must Not Have Pseudo Notes'. The first one requires that a line entity should touch the lines from the same entity class or subtype at both ends. The second one requires that one line must connect at least with two other lines at each end.

After the validation of the road network (network without topology errors), it was necessary to create the Network Dataset to perform the network analysis. In this operation, two cost attributes were considered: distance, in kilometers, and time, in minutes. Given that the analysis was performed for 'automobile' mode, a restriction related to the travel direction was considered through the Oneway attribute. VBScript expressions were defined for the unidirectional constraint attribute. Table 2 presents the evaluators and expressions considered for each direction of movement.

Table 2
Evaluators and expressions for each movement direction.

Script code		Allowed travel instructions
Restricted = False Select Case UCase ([Oneway]) Case "N","TF","T": Restricted = True End Select	Restricted = False Select C UCase ([Oneway]) Case "N","FT","F": Restricted = True End Select	FT or F = Travel is only allowed in the line direction (from-to). TF or T = Travel is only allowed in the opposite direction of the line (to-from). N = Travel is not allowed in any of the directions. Any other value = Travel is allowed in both directions.

Other spatial data

In addition to the road network information, the waste collection vehicle departure point (municipal warehouses), the exit point of the parish (towards the waste transfer station) and the location of Oleiros-Amieira's undifferentiated waste containers (information provided by the municipality) were considered and included in the model.

Regarding the green waste collection, the municipality proposed the location of new containers for the deposit of this type of waste in the more rural areas within the parish. Additionally, two available locations for a biomass plant installation were also proposed, in order to analyze the best location according to the spatial distribution of containers and population. This information was added to the model.

Analysis, results and discussion

Considering the road model, undifferentiated and green waste containers location and cleaning services needs, collection routes and the location of new containers and facilities were analyzed. For this purpose, 3 different scenarios were simulated to obtain shorter and faster collection and transportation routes, closest facility, service areas, best biomass plant location and OD (origin–destination) cost matrices.

Scenario 1: Waste collection route optimization for the current parish situation

As Oleiros-Amieira’s waste collection does not currently follow a defined strategy, for this scenario, an optimization analysis is performed to find daily collection routes with minimum transportation cost, considering no waste separation (current situation) and that one of the two municipality collection vehicles will be used to collect waste from this parish. Regarding the vehicles’ characteristics, both have a capacity of 19 tons (15 m^3) and are equipped with a compactor. The cost attribute considered in the analysis is time, since it is intended to determine how long it is necessary to collect the waste deposited in all the containers of the parish (376), as well as whether or not it would be possible to perform this collection on a single daily route with a single collection vehicle. The aim is to obtain the fastest route from the municipal warehouses (location of departure of the waste collection vehicle) to the exit point of the parish (towards the transfer station where the waste will be deposited). Thus, the start and end points of the waste collection route and the location of containers are considered in the analysis. Similar analysis using ArcGIS routing tools were performed by Lavigne et al., (2021, 2023) and Thiriet et al. (2020) to optimize waste collection in larger cities.

The analysis is performed on the basis of the assumption that would result in a long route. Thus, it would not be possible to perform it in just one trip, since only one vehicle is available for the waste collection. It is also considered that the capacity of the vehicle is sufficient to cover the collection of waste throughout an entire working shift (7 h). According to information from the municipality’s services, the production of waste per day for the parish does not generally exceed 8 tons (in the summer, when the population increases due to the presence of immigrants on vacation), containers have a capacity of 800 and 1100 L, are not considered always full, and collection is carried out daily in zone 1 and weekly in zones 2 and 3 (see Fig. 3). As a reference, the value recorded by the municipality’s services in 2022 was 1182.4 tons of waste collected throughout the municipality (composed of 10 parishes).

Using the New Route analysis tool, the network analysis resulted in a 936 km long route and a travel time of 1327 min (approximately 22 h). As initially predicted, it is not possible to collect the waste of all containers in a single working day. Because of this, it is necessary to define less extensive collection areas and several collection days, or even reinforce the waste collection fleet with a second vehicle. To develop a viable solution without increasing the vehicle fleet, the parish was divided into 3 distinct areas, so it is possible to find and optimize one day waste collection route for each of them. The division was based on two criteria: on the population distribution, i.e., urban (concentrated) versus rural (dispersed) areas, and on the territory coverage and travel distances. The first area, Zone 1 (1598 inhabitants), encompasses the containers located in and around the town of Oleiros, resulting in the need to collect the waste deposited in 221 containers; the second area, Zone 2 (244 inhabitants), includes the most rural and dispersed settlements located in the western part of the parish, with 79 containers; finally, the third zone, Zone 3 (238 inhabitants), also with rural and dispersed settlements, located in the eastern part of the parish, has 76 containers. For each of these 3 areas, a new route was defined using the same methodology initially adopted for finding a single total route for the entire parish. The route obtained for Zone 1 can be travelled in approximately 7 h and is 248 km long. For Zone 2, it was found a route with 285 km that can be travelled in approximately 6.5 h. Finally, for Zone 3, the optimized route has 272 km long and a travel time of 6.1 h (see Fig. 3). This is a possible solution that can be adopted in each of the defined areas since the workers’ daily working period is 7 h.

The main outputs, i.e., time required and distance travelled for each collection route, validate the viability of performing a daily waste collection with a single team and collection vehicle, considering the three areas proposed by the municipal representative. Taking as a reference that the most central area of the parish, corresponding to Zone 1, is where the largest number of inhabitants are concentrated and it generates an approximate daily volume of 3 tons of waste in the summer period, it is expected the need to perform the waste collection route, at least, twice a week. For the more rural areas of the municipality, corresponding to Zone 2 and Zone 3, a weekly collection is expected to be sufficient, meeting the needs of the population. A more rigorous assessment of the waste production volume over time (seasonal variation) or the installation of sensors to measure the containers fill level will allow to refine the optimization of waste collection operation, including the definition of the periodicity to be adopted according to the waste generation characteristics of each zone.

If a biowaste (green waste and kitchen waste) separation strategy is implemented in the municipality, the same approach can be applied

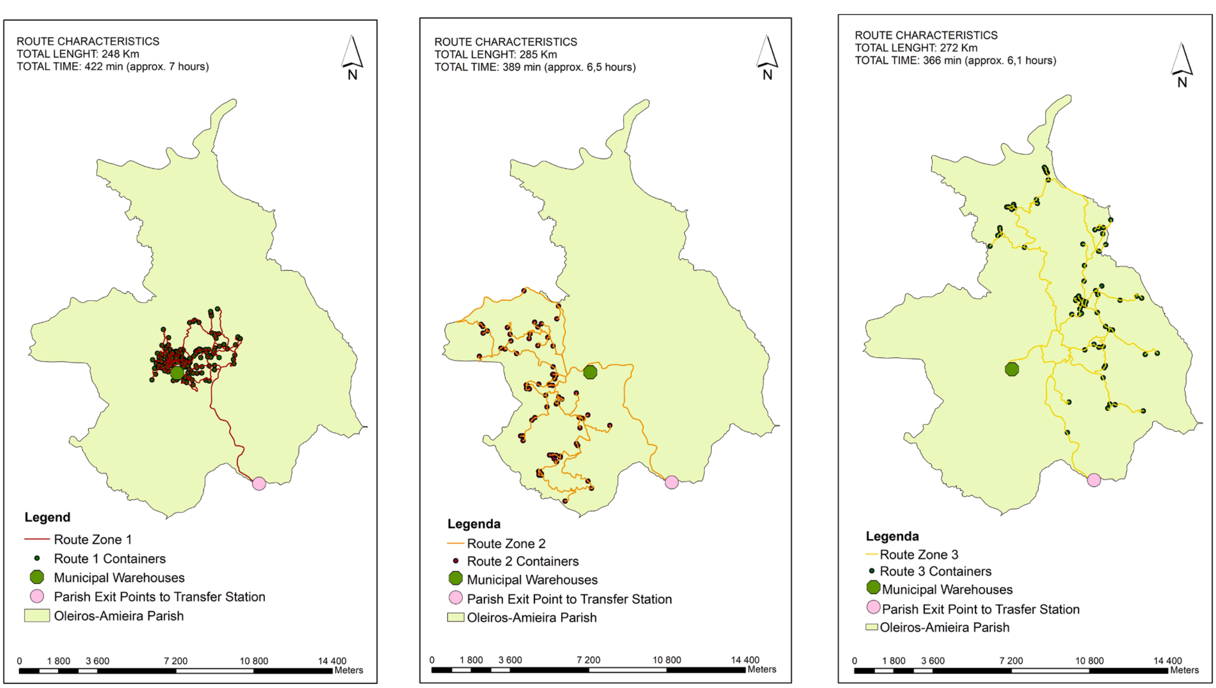

Fig. 3. Optimized waste collection routes for Zones 1, 2 and 3.

considering the location of the dedicated containers.

Scenario 2: Optimization of a new service of green waste collection and biomass plant location

The second analysis performed took into consideration the municipality's intention to install a set of containers for the disposal of green waste. The containers would be strategically placed next to the most rural settlements, where the use of burning by the population is a usual practice to eliminate agricultural and forest remnants. The analysis performed intends to find the travel times needed to reach the green waste containers, with the municipal warehouses as the departure location. For this purpose, the municipal representatives selected 17 locations spread throughout the study area for the installment of the green waste containers (see Figs. 4 and 5). The tool used for the analysis was the New Service Area functionality, having been defined as 'Facilities' the location of the municipal warehouses. This location corresponds to the vehicle's departure point for container maintenance and deposited material collection. In the analysis properties, time (minutes) was defined as impedance and were considered time intervals of 0–5, 5–10, 10–15, 15–20, 20–30 and 30–60 min. The results obtained allowed to conclude that none of the containers was located more than 20 min away from the municipal warehouses, allowing its maintenance through routes considered feasible in terms of time spent by the cleaning service team (Fig. 4). It is expected, if viable, that sensors will be installed to identify the exact moment when one or more containers are full up, triggering an analysis on the optimization and viability of the collection operation by the cleaning services.

Once the 17 containers for deposition of agricultural and forest remnants are implanted, the municipality should consider the construction of a biomass plant to process the collected green waste. As there are two industrial parks within the parish (industrial parks of Alverca and Açude Pinto), the possibility of locating the biomass plant in one of these parks is analyzed. The choice of the location, which already verifies accessibility, urban rules and facility size criteria, should take into account the following conditions: access to the largest number of containers within a maximum distance of 10 km and proximity to settlements with more population (more than 25 inhabitants). To include the population condition in the analysis, a container weight was defined:

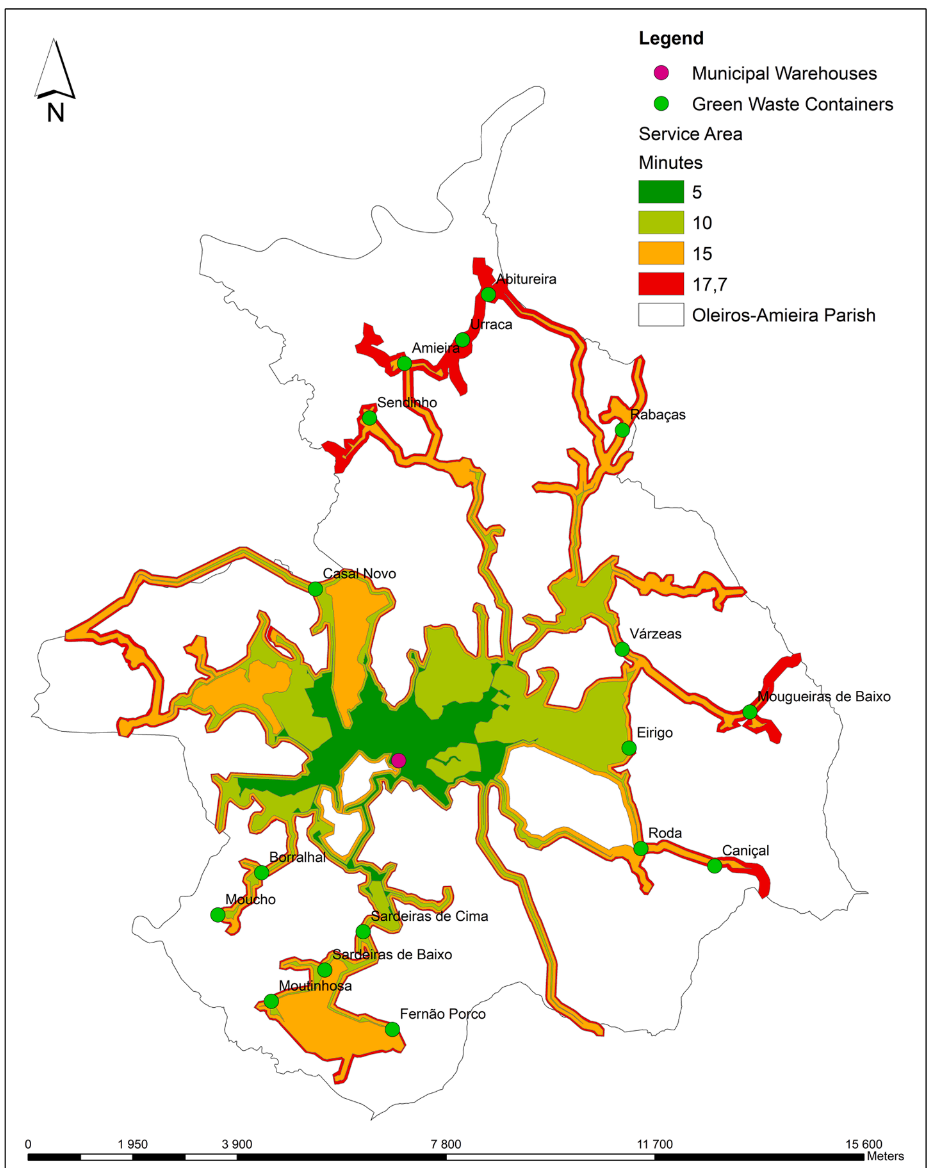

Fig. 4. Results of the New Service Area analysis for the green waste containers maintenance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

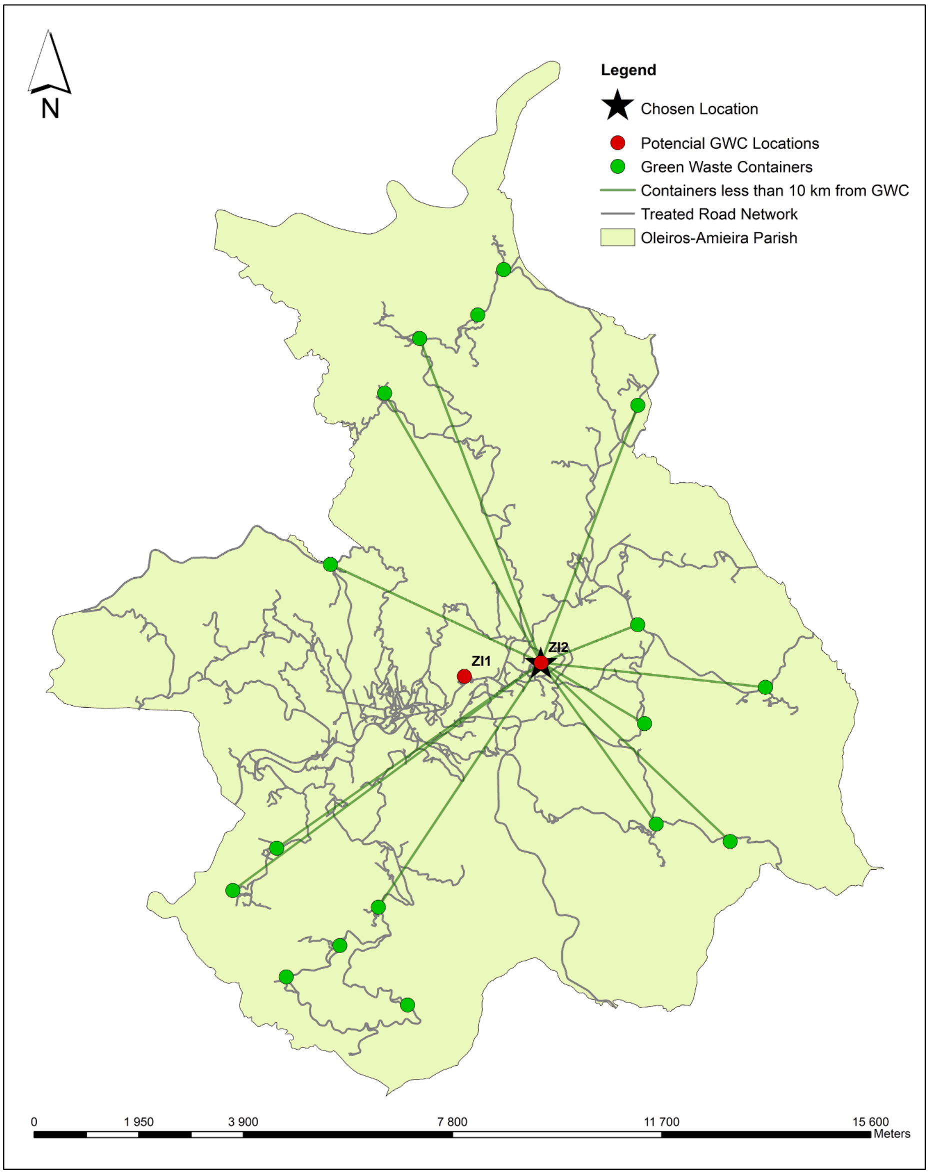

Fig. 5. Results of the New Location/Allocation analysis for biomass plant location.

1 for containers located near the less populated settlements and 2 for containers near the most populated ones. Choosing the Network Analyst's New Location-Allocation tool, the shapefile containing the two possible biomass plant locations was introduced as 'Facilities' and the shapefile with the green waste containers position as 'Demand Points'. Weight was considered through a specific 'Weight' attribute field. Considering the defined conditions, the results of the analysis indicated the industrial park of Açude Pinto (ZI2) as the most favorable location. Locating the biomass plant in this industrial park will allow to cover 12 of the 17 containers (see Fig. 5) for the defined criteria. On the other hand, the analysis of the Alverca industrial park (ZI1) location resulted in a coverage of 0 containers. Analogous optimal location analyzes using GIS tools, including the use of location-allocation functionality, are also referred by Chukwuma et al. (2021) and Kodba et al. (2023) to support optimal location of biogas/bioenergy plants.

Scenario 3: Other green waste related daily services

In this scenario, to support decision, the New Closest Facility and New OD Cost Matrix functionalities are used to analyze hypothetical emergency and municipal services' support situations. The OD cost matrix tool was also applied by Tampio et al. (2017) to analyze waste related scenarios, namely, to calculate the shortest transportation distance between a biogas plant and crop fields of farmers willing to use waste-based nutrients. In another study, Matthew and Spataru (2023) mention the adoption of matrix of distances to optimize capacitated vehicle routing problem (CVRP) using Python and Google's OR-tools solver.

In scenario 3, the New Closest Facility tool is used to evaluate a hypothetical scenario in which a civil protection team from the municipality comes across a fallen tree on a road. After tracing the tree and loading the material into a pickup truck, the team cannot immediately transport the material to the municipal warehouses, since several works are scheduled for the rest of the day. Therefore, they need to deposit the remains of the tree in the closest green waste container. In this scenario, the office technician that supports the cleaning services is contacted to perform a quick analysis. For the analysis, the location of the green waste containers must be used as 'Facilities' and the location of the civil protection team as 'Incident'. The analysis result will indicate a container located in the vicinity of the incident. The simulation of this hypothetical scenario was analyzed considering the civil protection team's location, shown in Fig. 6. For the considered location, the analysis showed that the closest container is located 3.2 km away, with

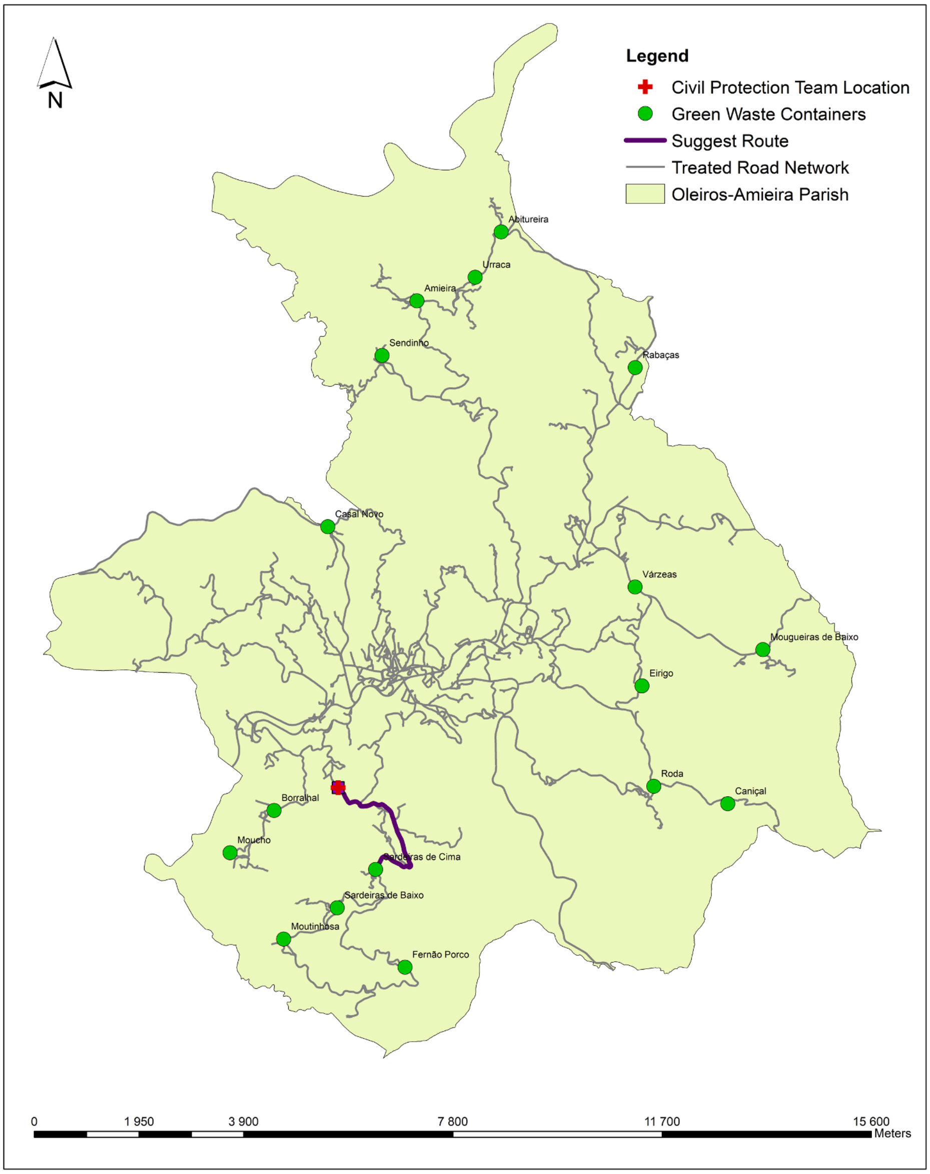

Fig. 6. Results of the New Closest Facility analysis to support decision – hypothetical scenario.

arrival at the site in about 3.5 min (Fig. 6).

Finally, the New OD Cost Matrix tool was used to analyze a hypothetical scenario, in which the municipality's cleaning team needs to monitor the state of one green waste container. However, due to a team training scheduled in 30 min at the City Hall, they need to select a container close to the municipal warehouses and the City Hall, at no more than 10 min away from both, since the monitoring operation takes about 10 min. In this analysis, the municipal warehouses and the City Hall were chosen as 'Origins' and the green waste containers as 'Destinations'. The analysis revealed that the team could choose one of the eight results presented in Fig. 7. The choice of a single green waste container will subsequently be made according to existing container monitoring records.

It should be noted that, if the network model is built and if the information regarding the location of undifferentiated/bio/green waste containers and points of interest for the operation of the municipality's cleaning service is available and organized, including points of interest related to other municipal services that can take advantage of this information, the analyzes described can be carried out very quickly, supporting the management of unforeseen situations in almost real time.

Conclusions

The optimization of biowaste collection as part of the waste reuse cycle has a positive and direct effect on the environment, economy and population. As the selective collection of biowaste will be an obligation in the EU space by the end of 2023, its management is currently one of the main concerns of municipalities. Considering the spatial component associated with the management of any kind of waste, GIS-based approaches are considered adequate for the comprehensive and rational assessment of biowaste collection and transportation. This management can be supported using GIS technologies, namely by taking advantage of the various network analysis functionalities available in several existing software.

In view of the above, the method described in this study provides the foundation for a powerful GIS-based operational planning tool and proved the feasibility and flexibility of the approach for optimizing numerous scenarios of biowaste collection and transport-based services in rural small sized municipalities. It allows the support of managers' decisions by obtaining optimized solutions based in real needs, resources and cost minimization, in order to boost municipal sustainable practices and adopt digital solutions. The approach can be also used by

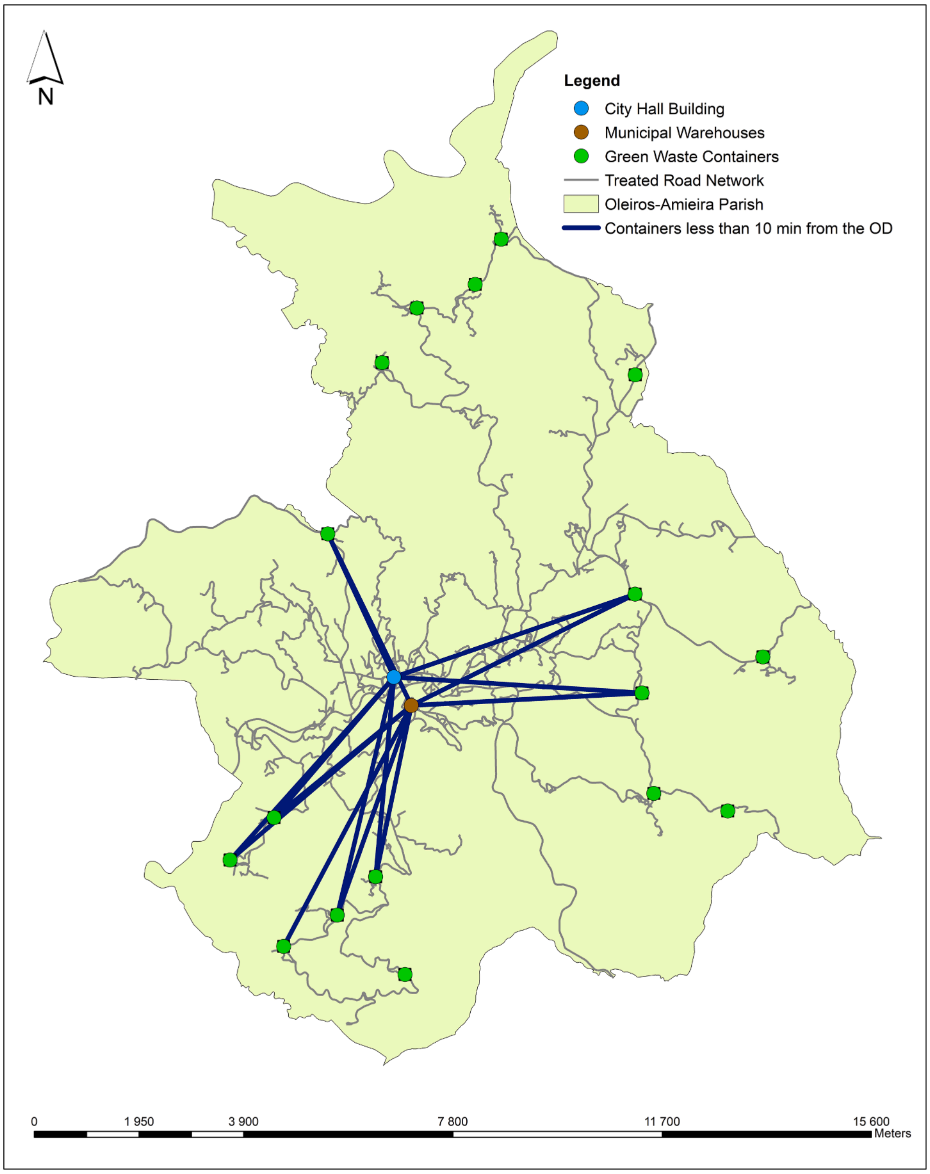

Fig. 7. Results of the New OD Cost Matrix analysis to support decision – hypothetical scenario.

policy makers to simulate waste collection and transportation scenarios and evaluate the impact of policy decisions on costs and resources.

Regarding the case study, the municipal waste collection optimization analysis performed allowed to conclude that, with the human and vehicle resources available in Oleiros-Amieira, it is not possible to carry out a daily waste collection that covers all of the parish's containers, which, due to the low population density, is not really necessary. A solution based on the parish division into 3 distinct areas, for waste collection purposes, was obtained. Considering the rural and forest nature of the analyzed parish, the possibility of implementing a small network of community green waste containers was also studied. This measure, along with the decrease of burnings, promotes the valorization of this material, since it can be used for biomass production. The analyses results revealed that it is possible to monitor the containers within travel times of up to 20 min. Assuming that this scenario achieves success and population acceptance, the creation of a biomass plant in one of the two industrial parks located in the parish was also considered. When implemented in the Açude Pinto industrial park, the material deposited in a larger number of containers can feed the biomass plant for a maximum travel distance of 10 km. Finally, the tool was also tested for two hypothetical unforeseen scenarios. The analysis of these situation allowed to prove the usefulness of the tool in providing almost real-time support to several municipal services (civil protection, cleaning, etc.) in unforeseen daily situations.

As the waste collection and transportation is not only essential to the population, but also one of the most expensive services under the responsibility of municipalities, it is expected that the application of the proposed approach will achieve balanced solutions in economic, environmental and social terms. This can enhance the joint commitment of municipalities and population in the pursuit for sustainability of biowaste collection and transportation services.

As further research, to get better insight into the waste collection problem and include dynamic spatio-temporal aspects in the analysis, this approach can be extended to include more detailed information, such as the location of available waste transfer and treatment facilities, land use and biowaste generation time series data. Another expected extension is to evolve to a GIS-based approach that can answer to the provision of a service 'on demand', allowing the creation of daily waste collection routes adapted to real needs, avoiding unjustified stops in empty or unfilled containers.

CRediT authorship contribution statement

Bertha Santos: Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing - original draft, Writing - review and editing. **Cláudia Mendes:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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