Multi-criteria GIS-based siting of an incineration plant for municipal solid waste

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ABSTRACT

Siting a municipal solid waste (MSW) incineration plant requires a comprehensive evaluation to identify the best available location(s) that can simultaneously meet the requirements of regulations and minimise economic, environmental, health, and social costs. A spatial multi-criteria evaluation methodology is presented to assess land suitability for a plant siting and applied to Santiago Island of Cape Verde. It combines the analytical hierarchy process (AHP) to estimate the selected evaluation criteria weights with Geographic Information Systems (GIS) for spatial data analysis that avoids the subjectivity of the judgements of decision makers in establishing the influences between some criteria or clusters of criteria. An innovative feature of the method lies in incorporating the environmental impact assessment of the plant operation as a criterion in the decision-making process itself rather than as an a posteriori assessment. Moreover, a two-scale approach is considered. At a global scale an initial screening identifies inter-municipal zones satisfying the decisive requirements (socio-economic, technical and environmental issues, with weights respectively, of 48%, 41% and 11%). A detailed suitability ranking inside the previously identified zones is then performed at a local scale in two phases and includes environmental assessment of the plant operation. Those zones are ranked by combining the non-environmental feasibility of Phase 1 (with a weight of 75%) with the environmental assessment of the plant operation impact of Phase 2 (with a weight of 25%). The reliability and robustness of the presented methodology as a decision supporting tool is assessed through a sensitivity analysis. The results proved the system effectiveness in the ranking process.

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1. Introduction

In spite of being equipped with modern technologies to comply with the very strict emission limits imposed by legislation, municipal solid waste (MSW) incinerators are still perceived as great pollutant sources. Because of that, an incineration plant erection often faces public reluctance in contrast with the acceptance of other more common energy utilities. In fact, according to Colebrook and Sicilia (2007), social opposition is one of main problems when locating any new MSW management plant.

A new MSW incineration plant (MSWIP) location is not an exception and, therefore, it may become a critical issue in the urban planning process due to the enormous amount of both data and qualitative information that may have to be taken into account in the decision process (see e.g. Khan and Faisal, 2008; Aragónes-Beltrán et al., 2010). Random or ill-defined locations may result in strong adverse impact from its operation on local communities and contribute to degradation of the surrounding environment.

Even when the installation complies with the regulated in-stack emission limits, a broader and more integrated perspective of its impact in the surrounding environment is required as its environmental performance strongly depends on local atmospheric conditions and terrain morphology. These conditions influence long-term emissions dispersion.

Hence, it is essential to perform the integration of environmental impact assessment in the pre-project stage of a MSWIP, and particularly during the decision making process itself (see Sumathi et al., 2008), rather than at its project stage, in order to make it environmentally responsible and socially acceptable, ensuring that any associate adverse impact is minimum or even neutral.

Siting a new MSWIP (or any other MSW treatment plant) is a very complex task requiring political decisions based on technical, economic, environmental, health, and social issues since, on one side, multiple and sometimes contradictory objectives are involved and, on the other, multiple alternatives may be available or, sometimes, the number of candidate alternatives is theoretically infinite. Such complexity requires the development of systematic, transparent and clear procedures that reduce the uncertainties, and support the decision makers to undertake sound decisions (Erkut and Newman, 1989).
It should be mentioned that each type of MSW treatment plant has its very own specificities and, consequently, requires the taking into account of particular decision-making criteria. Moreover, for the same type of waste treatment plant, such criteria are very case-sensitive varying from country to country and even from region to region in the same country. As reviewed by Aragónes-Beltrán et al. (2010), different authors have used different criteria according to their particular case study: technical, economic, environmental, social and plant operational costs (Khan and Faisal, 2008); natural factors (hydro-geological, geological and topographical), and artificial factors (accessibility, infra-structures, urban centres, villages and land use) (Sener et al., 2006); costs of transport, hazardous waste amounts and number of people in the bandwidth for hazardous waste type (Alumur and Kara, 2007); accessibility for motorway, distance from the nearest motorway, population, new roads erection requirements, impact and landscape, agricultural value, natural habitat protection (Nor ese, 2006); economic (land, personnel and energy costs), infrastructural (facility access, proximity to inhabited areas) and legal objectives (Queiruga et al., 2008). Despite the previous vast amount of criteria, Aragónes-Beltrán et al. (2010) proposed the grouping of those used in their work into plant exploitation costs, facilities and infrastructures, environmental issues and legal requirements.

However, as clearly stated by those authors, and following the work of Khan and Faisal (2008), such criteria identification and clustering is burdened with the subjectivity of the judgements made by the decision-makers and other participant actors since they are based on their personal knowledge and experience. This means that although some criteria may be universal for every MSW treatment plant (like the exploitation costs, facilities and infrastructures), others (environmental issues and legal requirements) are very case-sensitive. Because of that, tools developed to support decision makers must be flexible.

Besides the criteria, approaches for siting socially problematic facilities can also vary considerably. This siting subject has been object of many studies in the literature recurring to different approaches based on multi-criteria decision methods. Alumur and Kara (2007), Emek and Kara (2007) and Colebrook and Sicilia (2007), among other authors, solved multi-objective problems without using a set of pre-defined starting candidate sites. On the other hand, and starting from a small pre-defined set of candidate sites, Vuk et al. (1991), Cheng et al. (2002, 2003), Norese (2006) and Queiruga et al. (2008), among others, used multi-criteria decision analysis (MCDA) to solve siting problems.

Another approach for siting undesirable facilities that has been used in the literature is the Analytic Network Process (ANP), which requires as starting point a small number of alternative sites pre-defined for the waste treatment plant and considers the influences and interactions between criteria and alternatives, according to the knowledge and experience of the decision-maker (see e.g. Erkut and Newman, 1989; Khan and Faisal, 2008; Aragonés-Beltrán et al., 2010).

In turn, MCDA associated with Geographic Information Systems (GIS) for optimal siting of waste treatment facilities has also appeared lately in the literature but the vast majority of the works seeks optimal landfill siting – Siddiqui et al. (1996), Kao and Lin (1996), Kontos et al. (2005), Higgs (2006), Al-Jarrah and Abu-Qdais (2006), Sener et al. (2006), Gemiti et al. (2007), Chang et al. (2008) and Delgado et al. (2008). Chieu et al. (2008) and Chang et al. (2009) gave the first steps in MSWIP siting by proposing GIS-based methods to allocate compensatory funds for existing incinerators, which included environmental impact assessment. Although those works represent decision supporting tools giving relevance to the assessment of the environmental impact, they focused on the incineration plants operational stage rather than assessing the more valuable environmental impact as a part of the decision-making process itself.

It should be stated that the integration of GIS with MCDA techniques offers a powerful tool to facilitate and accelerate any siting process. GIS possesses unique capabilities for automating geospatial analysis (capture, store and manage large amounts of spatial data) and to perform analysis. Moreover, GIS describes intrinsically the influences between the criteria related to natural or artificial issues as, for example, morphology, hydrology, land cover, land use, actual distances, visual impact and pollutants dispersion. This is an advantage since it avoids the subjectivity of the judgements of decision makers in establishing the influences between some criteria or clusters of criteria. Additionally, when using GIS, each criterion can be divided into a sub-graduating system allowing for the decomposition of its weighting value for a defined region according to the degree by which that region respects that criterion. Finally, GIS allows visualising results through graphical representation.

Furthermore, MCDA is used to deal with the difficulties in handling large amounts of complex information supplying a consistent evaluation of the potential sites based on a variety of criteria. The analytic hierarchy process (AHP) introduced by Saaty (1980) is a widely accepted method in decision making problems involving multiple criteria in systems of many levels designed for priority identification.

The present study aims at developing a methodology to locate a new MSWIP by using AHP combined with GIS and applying it to in Santiago Island, Cape Verde, where the government intended to build a waste treatment facility, combining it with the production of potable water for the population, a commodity that lacks considerably in that region. Since there was not any pre-defined set of candidate sites for that waste treatment facility and the starting point was the entire area of Santiago, 991 km², the chosen approach had to combine flexibility, the possibility to use a sub-graduating system to narrow the choices and appropriate capacities of automating geospatial analysis. From the previous discussion, it appears that the methodology presented herein, combining AHP to estimate the relative importance weights of the identified evaluation criteria with GIS for spatial data treatment with a sub-graduating system, analysis and visualisation, which takes intrinsically into account the natural influences between the criteria avoiding as far as possible the subjectivity of the decision-maker judgements, constitutes a most adequate tool for the purpose. Evaluation criteria based on existing legislation, regulations, experiences and expertise, cover natural, socio-economic, technical and environmental aspects.

Most of the above-referred siting works presented in the literature did not use the environmental impact as a criterion; they rather used it a posteriori. On this matter, the innovative and challenging aspect of the presently methodology is the incorporation of the environmental impact assessment of the future plant operation during the pre-project phase, i.e. during the decision-making process of the MSWIP siting itself. Moreover, and due to the starting large area of analysis without any pre-defined set of candidate sites, the use of a two-scale approach, the global scale for a first siting refinement and the local scale for further refinement, constitutes another innovative feature. At the largest scale an initial screening identifies an inter-municipal region satisfying the socio-economic, natural and technical–environmental criteria (investment and plant operational costs, basic needs of population for potable water, land orientation for pollutants dispersion analysis and land cover to account for protected areas). Then, at a smaller scale within the previously identified region(s), a detailed suitability ranking based on social, legal, natural and technical criteria, and including the environmental impact assessment, is performed to refine the choice and end up with a small and limited set of candidate areas for siting the MSWIP.
In addition, a sensitivity analysis of the model is performed to assess the robustness and reliability of the generated results.

2. The 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 with a population of less than half a million.

Santiago Island, belonging to the leeward chain of the islands, is situated in the tropical zone between 14°50’ and 15°20’ of Northern latitude, and 23°20’ and 23°50’ of Western longitude, and has a sub-tropical arid climate, which is characterised by a short rainy season. It is the largest and most populated island, with a population that sums 55% of the total Cape Verde population.

Cape Verde is a developing country with constant economic growth, not possessing fuel resources and experiencing a shortage of potable water to satisfy the basic needs of the population. Diesel-based technologies cover more than 90% of the present demands for energy and potable water production. On the other hand, existing waste management is rather poor, with no separation at all for recycling, the unique treatment method being the disposal in uncontrolled open landfills with subsequent in loco burning for volume reduction (see Tavares et al., 2009 for more details), which is endangering the population health by potentiating epidemics like dengue fever, cholera and yellow fever. Because of that, one of the great challenges for Cape Verde is the establishment of an integrated and well functioning MSW management system that can guarantee proper treatment and disposal of waste (MAAF, 2004) and combining it with potable water production.

Limited availability in land resources in isolated island communities restricts to a large extent the waste disposal in landfills. Additionally, the absence (or the much too small scale) of a market for recycled materials and the distance from the continent often make of recycling and material recovery an unsustainable activity. Therefore, thermal treatment of MSW by incineration combined with energy recovery can be a reasonable and sustainable solution providing its integration within an overall waste management system.

The study to integrate MSW incineration with potable water production by seawater desalination was previously performed by Zsigraiova et al. (2009) and Tavares (2010), where the detailed characterisation of the MSW can be found (the physical average composition comprises 27% of mixed organic waste, 25% of mixed paper, 23% of mixed plastics, 15% of glass and 10% of metals).

Considering such hypothesis of thermal treatment by incineration with energy recovery, the total amount of waste available for incineration is estimated to be of 75 kton/year based on projections of waste generation and collection from all the municipalities of the island (see Zsigraiova et al., 2009 and Tavares, 2010 for details). It is expected that a plant with a capacity of 10 ton/h will allow for the treatment of all the collected waste.

The energy recovery combines production of heat and power, the heat being used for drinking water production through thermal desalination.

3. Siting methodology

A substantial multi-disciplinary evaluation process with multiple sets of criteria is required to identify the best available location(s) for a new MSWIP, the final goal of the present work, meeting the regulations requirements and minimising economic, environmental, health, and social costs.

To satisfy the mentioned final goal, the whole siting process is divided into several sequential steps:

- Identification of the evaluation criteria and sub-criteria or attributes associated with the problem and structuring them in a multi-criteria decision hierarchy;
- Assignment of grading values to the sub-criteria within the GIS framework;
- Determination of the relative importance weights of the sub-criteria and criteria by applying the AHP method;
- Aggregation of the criteria weights and attribute values to yield suitability scores of the areas; and
- Ranking of the areas according to their suitability scores.

Due to the starting large area of analysis without any pre-defined set of candidate sites, a situation that can be quite common, the use of a two-scale approach is proposed in this work. Such approach allows, first, for an initial screening of the studied area permitting to identify suitable inter-municipal zone(s) satisfying the most relevant socio-economic, technical and environmental requirements (named hereafter as global scale). Then, a more detailed evaluation of the previously identified zones is performed in the local scale procedure that comprises two phases. In Phase 1 a more detailed analysis to the zone(s) previously selected is carried out by applying important factors of natural, technical, economic, legal and social nature viewing the identification of the most suitable alternative areas. In Phase 2 the local scale procedure ranks these areas in terms of their environmental impact performance. This two-scale approach significantly reduces the effort required to collect and process additional information for the entire studied area.

The developed model to perform the above-mentioned multi-criteria analysis is based on GIS. All input data required for the analysis in the form of attribute map layers are extracted from several sources, the base-map of the entire studied area being available in a digital geo-referenced form of the scale 1:25,000. Additional layers include spatial information on infrastructure (road network and electrical grid), population, vegetation, and land-use.

The assignment of a suitability grade for every class in a certain attribute map is performed using ArcGIS® software. The resulting maps are then converted into raster cells representation of uniform grid sizes of 25 × 25 m², each cell containing a unique interpretable value.

Finally, to synthesize and automate the multi-criteria decision process in the GIS environment, the model uses Visual Basic programming language and suitability indexes for raster cells are assigned using GIS map algebra, the Spatial Modeller® tool.

3.1. Identification of the decision-making criteria

All stakeholders or actors were represented in the discussions to decide the evaluation criteria: technical staff from the Ministry of Environment, Ministry of Industry and Energy, Ministry of the Territory Administration and City-Halls; members of local assemblies; experts in the field, both public and private players; academics; and population organizations. It should be stressed that, as far as the Santiago population is concerned, and due to the experience of the death of relatives or friends because of dengue fever, it is common sense that waste has to be dealt with urgently and any solution is better than the present situation.

A thorough literature review and informal discussions with the actors, academics and experts working in the field, including private players assisted in developing the hierarchical structure displayed in Fig. 1 consisting of different sub-criteria or attributes that are aggregated as criteria and evaluated at two different scales. Each phase has its own objective and relevant evaluation criteria and sub-criteria.
The criteria used in the present case and their description are presented in Tables 1 and 2, respectively for the global and the local scales.

### 3.2. AHP method

Once the evaluation attributes are defined they must be combined into larger groups, the sub-criteria or criteria (see Fig. 1), in order to assess the land suitability for a MSWIP siting. This aggregation procedure, performed herein using the AHP method, plays a crucial role on the degree that each criterion influences the final suitability determination and avoids a large amount of direct pairwise comparisons.

AHP decomposes the complex decision problem into simpler and more understandable ones, so that one can analyse separately each part and then integrate them again in a logical manner. A pairwise comparison is used, where only two criteria and the importance between them are considered at a time. This way, it is more likely that a robust set of criteria weights will be produced. Paired elements are verbally judged against each other in terms of their importance for the objective they are contributing to and the 9-point scale of Saaty (2000) is used to quantify the procedure.

Once all pairwise comparisons are carried out at every level their values are arranged in the square matrix \( A \), Eq. (1), each cell containing the evaluation for each possible pair.

![Fig. 1. The hierarchical structure of the MSWIP evaluation methodology.](image)

### Table 1

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Attribute (thumb rule)</th>
<th>Criteria assessment description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Waste transportation costs (the lower the total cost of transportation the better as this reduces the exploitation costs)</td>
<td>Assesses the cost of waste transportation to the MSWIP, considering both the travelled distance and the amount of waste transported. The latter depends on the waste generated and, therefore, on the demography</td>
</tr>
<tr>
<td>A2</td>
<td>Distance from electrical grid (the closer the electrical grid the better as this reduces the investment costs)</td>
<td>Assesses the required investment costs that ensure the transmission of the produced electricity to the existent national electrical network</td>
</tr>
<tr>
<td>A3</td>
<td>Distance from coast line (the closer the coast line the better as this reduces both the investment and the operation costs)</td>
<td>Assesses the required investment and operating costs of the potable water production (by seawater desalination) and cooling water pumping</td>
</tr>
<tr>
<td>A4</td>
<td>Fly ash transportation costs (the closer the monofill the better as this reduces the environmental operation costs)</td>
<td>Assesses the cost of transportation of the resulting fly ash from incineration, in the flue gas treatment line, to a hypothetical monofill for ash disposal required from an environmental point of view</td>
</tr>
<tr>
<td>A5</td>
<td>Potable water demand (the higher the population concentration and lack of local water resources the more important becomes this criterion)</td>
<td>Measures the need to satisfy the population’s basic commodity of potable water from seawater desalination. Its inclusion views the overcome of the natural and very strong scarcity of resources of drinking water in Santiago due to its climate</td>
</tr>
<tr>
<td>A6</td>
<td>Land orientation (very case-dependent)</td>
<td>Assesses the global effect of the land orientation to the wind on the pollutants dispersion due to the exposure of the incineration plant stack to the atmospheric conditions</td>
</tr>
<tr>
<td>A7</td>
<td>Land cover (very case-dependent)</td>
<td>Measures the importance of the existing vegetation types and their spatial distribution. Correlation of land type and economic activities, like agriculture and pastures, is taken into account. Protected natural parks, deep valleys, and some volcanic formations are also taken into consideration</td>
</tr>
</tbody>
</table>

\(^4\) Bottom ash is a by-product of the incineration process to be sold for other purposes and, therefore, it was not considered herein as criterion.
The resulting eigenvector of weights corresponds to the maximum eigenvalue $\lambda_{\text{max}}$, which is calculated by solving the following characteristic equation, Eq. (2b):

$\det(J - A) = 0.$

(2b)

To obtain relative weights the eigenvector elements are normalised by dividing them by their sum, Eq. (2c):

$W_j = \frac{v_j}{\sum v_j}.$

(2c)

In the previous equation, $W_j$ is the relative importance weighting value of the criterion $j$ and $v_j$ is the $j$-th element of the eigenvector $\nu$.

The relative weights yielded by the AHP method are combined with GIS to arrive to the areas classification in terms of their overall suitability. For that, a suitability index ($SI_i$) is determined for each raster cell and each hierarchy level by aggregating the relative importance weighting values, as expressed by Eq. (3).

$SI_i = \sum W_j G_{ij}.$

(3)

In Eq. (3) $SI_i$ is the suitability index value of the cell $i$, $G_{ij}$ is the grading value of the cell $i$ under the criterion $j$ (as displayed in Table 3) and $n$ is the number of criteria at a given hierarchy level.

If the decision hierarchy is decomposed into more than one level, which is the present case, the relative importance weights have to be aggregated through the whole hierarchical structure.

Higher suitability index values for a given cell mean larger probability to become a part of a MSWIP site.

Once the suitability indexes are assigned the entire studied area can be ranked. Areas with low suitability are considered inadequate for MSWIP siting.

3.3. Intermediate results for global scale

3.3.1. Assigning grading values to the sub-criteria within the GIS

Since the suitability degrees for a specific criterion or attribute may differ, a grading system is used to express such variability. For that, values ranging from 0 to 10 are assigned based on data from the technical literature, if not otherwise stated. This means that a certain area is considered unsuitable for a certain attribute if graded with 0 and is excluded from further examination.

Table 3 resumes the grading values attributed to each sub-criterion within GIS. The following considerations illustrate the procedures adopted for each of the sub-criteria.

3.3.1.1. Waste transportation costs. The waste transportation is an important issue that constitutes an inseparable part of an integrated MSW management system, present at each of its stages. The economic and environmental problems associated with waste transportation include fuel consumption, and significant amounts of emitted pollutants.

The cost of MSW transportation is estimated by using the 3D-GIS model of Tavares et al. (2009), which optimises routes for the lowest fuel consumption taking into account both the effect of road inclination and vehicle load.

The total waste transportation cost for each municipality, $TrCost_i$, is expressed by Eq. (4):

$\min(TrCost_i) = \frac{\sum_{j=1}^{n} Q^\text{msw}_{ij} (TFC_{ij} + TFC_{ij})}{VC}.$

(4)

In the previous equation $n$ is the total number of municipalities, the ratio $Q^\text{msw}_{ij}$ stands for the number of turn trips from the municipality $j$ to $i$ as $Q^\text{msw}_{ij}$ is the total MSW quantity transported from the municipality $j$ to $i$ and $VC$ is the vehicle capacity. Moreover, $TFC_{ij}$ is the fuel consumption for routing from the municipality $j$ to $i$ for fully loaded vehicle, and $TFC_{ij}$ is the fuel consumption for routing from the municipality $i$ to the unloaded vehicle.

This allows for the definition of the quantitative grading of Table 3.

The results for this criterion are displayed in Fig. 2a showing clearly that the location of the MSWIP is necessarily close to Praia municipality since waste generated is by far the largest one (37 kton/year).
3.3.1.2. **Distance from electrical grid.** This criterion grades the potential locations of the MSWIP according to their radial distances from the national electrical network taking the relief into account (see Table 1). Fig. 2b shows the results illustrating clearly the penalty introduced by the much higher costs involved in locating a MWSP at zones with considerable relief changes (Pico D’ Antónia at the central mountainous region).

3.3.1.3. **Distance from the coast line.** This criterion is graded similarly to the previous one and Fig. 2c shows the results.

3.3.1.4. **Fly ash transportation costs.** Fly ash is a hazardous pollutant requiring special attention from both the environmental and social points of view. Because of that it was considered that fly ash is removed from the incinerator flue gases by using the best available technology of post-incineration gas treatment, and then it is sent to a hypothetical dedicated monofill. Therefore, the criterion used, similarly to that of waste transportation, is the fly ash transportation cost.

Since this monofill is inexistent, we assumed that its erection is another and considerably different siting problem and, therefore, it is not considered here.

Eq. (5) is used to calculate the fuel consumption from the municipality where the MSWIP might be located to all the other municipalities where the monofill might supposedly be sited. Since we do not know the actual location of the monofill, a conservative approach is required and the fly ash transportation cost is therefore taken as the maximum calculated cost:

\[ TFFaC_i = \max(TFFaC_{ij} + TFFaC_{ij}), \quad (j = 1, \ldots, n) \]  

(5)

In the previous equation, \( TFFaC_i \) is the total fly ash transportation cost for municipality \( i \) where the MSWIP might be located, \( n \) is the total number of municipalities, \( TFFaC_{ij} \) is the fuel consumption for routing from the municipality \( i \) to \( j \) for fully loaded vehicle, and \( TFFaC_{ij} \) is the fuel consumption for routing from the municipality \( j \) to \( i \) for the unloaded vehicle.

This procedure is repeated for each municipality \( i \) allowing for the definition of the quantitative grading of Table 3.

The results are shown in Fig. 2d. As it can be seen from this figure, this criterion yields the central part of the island as the best one to locate the MSWIP.

3.3.1.5. **Potable water demand.** Due to climate conditions and the lack of potable water, its demand was selected as criterion for the MSWIP siting.

Knowing on a yearly basis for each municipality the water consumption per capita (WCPC, in m³/inhabitant), the number of inhabitants (NH), and the available drinking water sources (AVW, in m³), the required water production (RWP, in m³) is estimated by:

\[ RWP = WCPC \times NH - AVW \]  

(6)

According to the results depicted in Fig. 2e, the municipalities with the maximum water demands are Praia city (2246,000 m³), followed by Santa Catarina city (430,000 m³).

3.3.1.6. **Land orientation.** Four great morpho-ecological blocks (designated as A, B, C and D in Fig. 2f) divide the island (Castanheira Diniz and Cardoso de Matos, 1986), expressing distinct features in terms of relief morphology, hydrology and climatic zones distribution. All blocks descend to the ocean from the central line passing the island in northwest–southeast direction. Data from the National Institute of Meteorology and Geophysics (INMG 2004–2008) evidence the yearly prevalence (90%) of the northeast trade winds with the consequent predominant potential for pollutants dispersion in the direction from the East coast to the inside land.

### Table 3: Grading values for sub-criteria within GIS.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Grading scale</th>
<th>Units</th>
<th>Attributes</th>
<th>Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 – Waste transportation costs (costs in terms of freight)</td>
<td>Equal intervals within the range each of 50 kg span</td>
<td>&gt;900</td>
<td>kg –</td>
<td>A</td>
</tr>
<tr>
<td>A2 – Distance from electrical grid</td>
<td>Equal intervals within the range each of 1000 m span</td>
<td>&gt;9000</td>
<td>m –</td>
<td>A</td>
</tr>
<tr>
<td>A3 – Distance from coast line</td>
<td>Equal intervals within the range each of 1000 m span</td>
<td>&lt;1000</td>
<td>m –</td>
<td>A</td>
</tr>
<tr>
<td>A4 – Fly ash transportation costs (in terms of fuel consumption)</td>
<td>Equal intervals within the range each of 50 g span</td>
<td>&gt;850</td>
<td>g –</td>
<td>A</td>
</tr>
<tr>
<td>A5 – Potable water demand</td>
<td>Equal intervals within the range each of 50,000 m³ span</td>
<td>&gt;0.5</td>
<td>m³</td>
<td>A</td>
</tr>
<tr>
<td>A6 – Land orientation</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>A</td>
</tr>
<tr>
<td>A7 – Land cover</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>A</td>
</tr>
<tr>
<td>A8 – Distance from road network</td>
<td>Equal intervals within the range each of 200 m span</td>
<td>&gt;1800</td>
<td>m –</td>
<td>A</td>
</tr>
<tr>
<td>A9 – Distance from coast line</td>
<td>Equal intervals within the range each of 200 m span</td>
<td>&lt;200</td>
<td>m –</td>
<td>A</td>
</tr>
<tr>
<td>A10 – Terrain slope</td>
<td>&gt;45</td>
<td>30–45</td>
<td>25–</td>
<td>A</td>
</tr>
<tr>
<td>A11 – Terrain elevation</td>
<td>&gt;360</td>
<td>40–</td>
<td>5–</td>
<td>A</td>
</tr>
<tr>
<td>A12 – Distance from urban centres</td>
<td>&lt;400</td>
<td>Residential, historical, touristic, industrial, agricultural, wet land</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>A13 – Land-use type</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>A</td>
</tr>
</tbody>
</table>

(block A, and partially block B and D). In turn, the West coast (block C) is more protected.

Furthermore, block A is the least arid one, this being the reason to be naturally selected for population settlements and major rural development. By contrast, block C is drier as it is oriented and descending to the ocean, followed by the block D in the north and block B in the south, which is the driest.

Combining such effects the final grading is that of Table 3 and the results are displayed in Fig. 2f.

3.3.1.7. Land cover. This criterion reflects the importance of existing vegetation types and their spatial distribution, which may need to be preserved and result from the correlation between the altitude and the land communities. Conformable to the situation in the studied region, the humid and sub-humid land communities are the best island regions for agriculture and pastures, and therefore considered less suitable for MSWIP siting. The semi-arid land communities are treated as suitable, and the arid land communities close to the coast line are considered the most suitable for a MSWIP siting. The vegetation of the protected natural parks, deep valleys, and some volcanic formations are unacceptable for a MSWIP location and, therefore, are graded with 0. The spatial map of the results is displayed in Fig. 2g.

The evaluation criteria for the global scale are grouped into three main categories: investment and operation costs, social issues and environmental and legal issues, each category possessing the attributes illustrated in Fig. 1.

3.3.2. Relative importance weights and results for global scale analysis

Table 4 resumes the relative importance weights of all criteria and attributes involved in the global scale analysis. The values of the pairwise matrices proposed to the working group were based on those from the literature for similar criteria (see e.g. Siddiqui et al., 1996; Kontos et al., 2005; Sener et al., 2006; Khan and Faisal, 2008; Aragonés-Beltrán et al., 2010). Then, the final values were always approved by consensus between all the intervening actors.

The main diagonal values are equal to unity since they refer to comparison of each criterion with itself.

![Spatial attribute maps yielded by the global scale analysis.](image)

Table 4

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Relative weights (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment and operation costs</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>48</td>
</tr>
<tr>
<td>Social issues</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>41</td>
</tr>
<tr>
<td>(potable water demand)</td>
<td>1/5</td>
<td>1/3</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Environmental and legal issues</td>
<td>SUM</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-criteria for each criterion</th>
<th>Investment &amp; Operation costs</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste transportation costs</td>
<td>1/7</td>
<td>1</td>
<td>1/3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Distance from electrical grid</td>
<td>1/3</td>
<td>1/5</td>
<td>1/3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Distance from coastline</td>
<td>1/7</td>
<td>1/3</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fly ash transportation costs</td>
<td>SUM</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environmental and legal issues</th>
<th>Land orientation</th>
<th>Land cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>SUM</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

The evaluation criteria for the global scale are grouped into three main categories: investment and operation costs, social issues and environmental and legal issues, each category possessing the attributes illustrated in Fig. 1.
and operation costs themselves). This result incorporates a political
decision expressing that the waste transportation costs is the most
important decision factor for the community at this stage of a
MSWIP siting.

The following step of the siting process is to classify the areas in
terms of their suitability with respect to the initial inter-municipal
zone selection by aggregating the obtained relative importance
weight values. This initial screening of the studied region reveals
that the Praia municipality seems to be the most appropriate for
the erection of a MSWIP, as shown in Fig. 3.

3.4. Local scale analysis: Phase 1

3.4.1. Assigning grading values to the sub-criteria of Phase 1 within the GIS

3.4.1.1. Distance from road network and distance from coast line. Similarly to that done for attributes related to distances at
global scale, terrain morphology (slope) has also to be taken into
account at the local scale procedure together with the radial dis-
tance. This is particularly important for irregular lands. The same
grading scheme used at the global scale is adopted here, as de-
picted in Table 3.

3.4.1.2. Terrain slope. Areas with sharp slope are not technically
suitable for an industrial facility erection. The grading was based
on the premise that the flatter the area, the greater its suitability
for a MSWIP construction as given in Table 3.

3.4.1.3. Terrain elevation. As far as the elevation attribute is con-
cerned, sites located at higher elevations represent some con-
straints due to the need for sea water pumping. The grading
values applied for this criterion are presented in Table 3.

3.4.1.4. Distance from urban centres. A MSWIP should not be built
up inside inhabited zones. The direct radial distance from urban
centres and population settlements are grading elements for this
attribute as given in Table 3.

3.4.1.5. Land use. The land-use represents a degree of economic
activities and population density associated with the area under
study. The different land-use types received different grading val-
ues considering their respective economic activities and the level
of population density. The residential, tourist areas and historical
sites, seaport and airport are considered inappropriate for MSWIP
siting and are, therefore, graded with 0. The same is applied to
wet land as they are sensitive ecosystems. The other land-use
types are assigned grades as given in Table 3.

3.4.2. Results for Phase 1

The evaluation factors specified for this phase are grouped into
three main categories: proximity of infrastructures and seawater,
natural terrain morphology and social and legal issues, each possessing
the attributes shown in Fig. 1.

Similarly to that presented for the global scale, pairwise com-
parisons are made for the elements of the decision hierarchy at this
local scale phase. The relative importance of the proximity of infra-
structures and seawater, natural terrain morphology and social and
legal issues criteria were assigned. Within each of these three cri-
teria, the relative importance was also assigned to each associated
attribute, as illustrated in Table 5.

Then the suitability classification of the areas within Praia
municipality is carried out by aggregating the relative importance
weights of Phase 1 criteria resulting in a more refined areas suit-
ability ranking given in Fig. 4d.

3.5. Local scale analysis: Phase 2

3.5.1. Environmental impact

The criterion of environmental impact is applied to the entire
zone selected at the global scale (the area pointed out with a rect-
gle in Fig. 3), the results being aggregated with the mentioned
preliminary suitable areas (outcome of the non-environmental fea-
sibility of Phase 1) to produce a composite MSWIP suitability map.

This criterion is particularly important and constitutes one of
the contributions of the present work as it is included in the
decision-making process itself. It is introduced to evaluate the
environmental effects of the MSWIP operation and comprises
two sub-criteria: air pollution and visibility.

The zone selected by the initial global screening is covered by a
grid system where each node represents a potential location of the
plant stack. This grid is organised in a Cartesian network with a
distance of 400 m between each pair of stacks.

3.5.1.1. Air pollution. MSW incineration plants, as other power
plants and unlike waste disposal to landfills, are mainly concerned
for their emissions to air. Emissions to water are not relevant, ex-
cept the disposal of fly ash trapped in the flue gas cleaning equip-
ment, as plants usually work with a closed water loop regime.

Emitted pollutants from the MSWIP operation are dispersed in
the atmosphere and the resulting concentrations depend on sev-
eral factors, such as the distance from the incineration plant, the
topography, the wind speed and direction and other climatic con-
ditions, the stability of the substances and their residence time in
the atmosphere.
The pollutants effect is quantified through the use of the EPA atmospheric dispersion models (US EPA, 1999) that have been widely used to simulate air pollution at ground level originating from an industrial plants (Chiueh et al., 2008; Chang et al., 2009). In the present case, and to determine yearly exposure to pollutants emitted from a given plant location, considering the stack as a stationary point source represented by a node in the aforementioned grid, the Industrial Source Complex Short Term (ISCST3) dispersion model is applied.

Two airborne pollutants, SO$_2$ and NO$_x$, are evaluated because the exposure to these acid components causes direct negative effects to the population health and the environment in general (e.g. lower agricultural yield, forest die-back or buildings damaging). The magnitude of the impact on the adjacent or more distant environment is directly dependent on atmospheric conditions for dispersion. In contrast, this would not be the case of the emitted CO$_2$, whose effect is global and is defined by the waste composition.

The effect of the pollutants emitted by the entire grid of stacks is characterised through modelling pollutant receptors that absorb the impact at ground level of the dispersion model. Such receptors are organised in a grid in a Cartesian network distancing 200 m from each other. Hence, taking into account the 400 m distance between adjacent emitting stacks, each emitter is surrounded by eight neighbouring receptors.

Use of such modelling allows for comparison against the ambient air quality standards in force, namely the EU directive 1999/30/EC on limits for certain pollutants (EC, 1999) and World Health Organisation (WHO) guidelines on air quality (WHO, 2006). To aggregate the impact derived from different air pollutants, the value of emission dispersion at each receptor location (AQ$_i$) is calculated through Eq. (7a).

$$AQ_i = \frac{1}{m} \prod_{k=1}^{m} \left( \frac{P_{ik}}{C_k} \right)$$  \hspace{1cm} (7a)

In Eq. (7a) $m$ is the total number of pollutants to be analysed (two in the present case), $P_{ik}$ is the individual impact generated by pollutant $k$ at receptor location $i$, expressed by the ground-level concentration value estimated by the ISCST3 model and $C_k$ is the annual limit concentration value in ambient air for a given pollutant $k$. According to Council Directive 1999/30/EC (EC, 1999) and WHO (2006) values of $C_k$ are 40 $\mu$g/m$^3$ (293 K, 101.3 kPa) for NO$_x$ and 20 $\mu$g/m$^3$ (293 K, 101.3 kPa) for SO$_2$.

The previous procedure yields a pollutant dispersion map for each stack location accounting for the emission effects at each receptor location.

Impacts from the proposed development are only of potential significance, regarding the sensitivity of receptors, if the predicted contribution increases the risk and hazard from long-term exposure to levels greater than those considered acceptable in the risk characterisation (EC, 1999; WHO, 2006). However, there is no
universally recognised definition of what constitutes significance and, therefore, a number of approaches can be used, particularly because some guidance can be found from a range of regulatory authorities and advisory bodies (NRCA, 2006).

The approach adopted to assess and characterise the significance of the predicted effects from a given candidate stack location on the air quality consists of determining the stack impact index ($SII$) on the receptors situated inside inhabited areas only for such candidate stack, as defined by Eq. (7b). The procedure is applied to all potential stack locations, resulting in assigning a $SII$ value to each stack location in the grid. The higher the $SII$ value, the higher the negative air pollution impact.

$$SII = \max(AQ_i)$$ (7b)

The used categories corresponding to a five level even-number grading are presented in Table 6.

Finally, the spatial attribute map of air pollution impact is generated based on the obtained $SII$ values, as illustrated in Fig. 5a, where the most suitable areas in terms of air pollution impact receive a ranking value of 10 while non-suitable areas are ranked with a value of 1. This means that the aggregation methodology performs an inversion of the grading values attributed to the stack air pollution impact.

3.5.1.2. Visibility. The distance at which the structure is visible depends on its height, presence of existing intervening structures and local topographic conditions, such as relief and vegetation coverage.

A simplified approach is applied to account for this effect, being assumed that the plant has aesthetic characteristics similar to other industrial facilities and the stack is the tallest structure among all associated facilities comprising the MSWIP. This sub-criterion is expressed by the visibility of each potential stack point location taken into account the surface morphology and direct distance from an observation point (because of its mitigating effect on visual effects of any construction development). Grading values between 1 and 10 are used for such classification and are displayed in Table 6. Moreover, as displayed in Table 6, special sites for observer locations are also graded. Combining the visibility and distance raster maps, a particular stack visibility map is produced.

The visual impact of a given stack location $p$ is represented by the visibility impact index ($VIp$) derived from the stack visibility map as expressed by Eq. (8):

$$VIp = \frac{\sum_{j=1}^{m} \eta_j G_{rj}}{\sum_{j=1}^{m} \eta_j}.$$ (8)

In Eq. (8) $\eta_j$ is the number of visible raster cells of the visibility category $j$, $G_{rj}$ is a grading value assigned to the visibility category $j$ and $m$ is the total number of visibility grading categories.

Similarly to air pollution evaluation, this procedure is applied to all potential stack locations, resulting in assigning a $VI$ value to each stack location in the grid. This spatial attribute map is based...
on the calculated VI values. The higher the VI value, the higher the negative aesthetic impact. Moreover, the most suitable areas for the plant siting receive a ranking value of 10, while those non-suitable areas have a value of 1 (the aggregation methodology performs an inversion of the grading values attributed to the stack visibility impact), which results in the spatial map of visibility shown in Fig. 5b. It is clear from this figure that the zones more distant and less visible from inhabited areas due to terrain morphology are more suitable and thus receive high index of visibility.

Then, the determined relative importance weights for the decision elements of the environmental impact in Phase 2 of the local scale analysis are given in Table 7.

From the two sub-criteria characterising the environmental impact, air pollution and visibility, the first one has the highest weight (75%) to evidence that the incinerator operation impact is perceived as a very important and serious issue.

The final spatial map of the environmental impact is displayed in Fig. 5c.

3.5.2. Final siting suitability

The whole evaluation is not completed until Phase 1 and Phase 2 results are not put together. The final suitability rank map, based on the defined relative importance weights for the decision elements as given in Table 7, is generated and given in Fig. 6.

Under the applied ranking scheme the highest ranked areas (say, those with ranking 8–10) are expected to be the best for siting a MSWIP.

As it can be seen from Fig. 6, in general the effect of the included environmental impact is visible in spite of its relatively small significant importance of 25% (see Table 7). With regard to the highest ranked areas resulting from Phase 1 (see Fig. 4d), they are maintained or reduced to a certain extent due to environmental impact.

The results obtained allow inferring that the relative importance of the chosen criteria for the studied case is reasonable. Nonetheless, other criteria could have been selected, as the decision making process is considerably subjective, especially in a complex problem as it is the MSWIP siting one. Furthermore, the relative weight of a decision criterion may affect the final ranking and the subsequent evaluation results. Because of that, the sensitivity analysis presented below was performed.

3.6. Sensitivity analysis

To assess the reliability of the proposed methodology, considering the above-mentioned subjectivity, different weight sets are de-

Table 7
Pairwise matrix developed for the local scale Phase 2.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1</th>
<th>2</th>
<th>Relative weights (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-environmental feasibility</td>
<td>1/3</td>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>1/3</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>SUM</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Environmental impact</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Air pollution impact</td>
<td>1/3</td>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td>Visibility impact</td>
<td>1/3</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>SUM</td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Previously studied scenario is highlighted.

Table 8
The relative importance weighting scenarios for Phase 1.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximity of infrastructures and seawater</td>
<td>1 2 3 4 5 6</td>
</tr>
<tr>
<td>Natural morphology</td>
<td>64 64 26 10 26 10</td>
</tr>
<tr>
<td>Social and legal issues</td>
<td>26 10 64 64 10 26</td>
</tr>
<tr>
<td>SUM</td>
<td>100 100 100 100 100 100</td>
</tr>
</tbody>
</table>

Previously studied scenario is highlighted.

Table 9
The relative importance weighting combinations for Phase 2.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-environmental feasibility</td>
<td>75 50 25</td>
</tr>
<tr>
<td>Environmental impact</td>
<td>25 50 75</td>
</tr>
<tr>
<td>SUM</td>
<td>100 100 100</td>
</tr>
</tbody>
</table>

Previously studied combination is highlighted.

Fig. 6. The spatial map of areas suitability ranking (Phase 2 local scale result).
fined and applied to investigate and understand their influence on the overall results. Such sensitivity analysis is carried out at the local scale for both Phase 1 and Phase 2 of the decision hierarchy.

For Phase 1, six scenarios are defined using different relative importance weights for the main decision criteria (proximity of infrastructures and seawater, natural terrain morphology and social and legal issues). For each scenario a different decision criterion is given the greatest importance, as presented in Table 8 (note that the highlighted Scenario 2 corresponds to the previously studied conditions).

Then, the sensitivity analysis continues for Phase 2 where three combinations are established by varying the relative importance weights of both non-environmental feasibility and environmental impact criteria as given in Table 9 (note that the highlighted Combination 1 corresponds to the previously studied conditions).

Each combination was applied to each of the above-mentioned Phase 1 scenarios resulting in 18 different studied situations.

In Phase 1, although not graphically presented herein, Scenario 1 seems to be the most conservative one in terms of availability of suitable areas and the level of high ranking, whereas Scenario 6 results in significantly large areas of the highest ranks.

The whole evaluation must be completed by ranking the suitability of the areas identified in the previous step as far as their environmental performance is concerned, that is Phase 2.

For Scenario 2 (see Fig. 4d for the results of Phase 1), the results for Combination 1 (stressing the non-environmental feasibility) were already presented in Fig. 6. Then, Fig. 7a and b exhibit the results for Scenario 2, respectively, for Combination 2 (equal importance for both decision criteria) and Combination 3 (stressing the environmental impact). Although figures may differ, there are areas that kept their high ranking values regardless the combination. Similar trends are observed for all the other studied combinations.

The final result of the present sensitivity analysis is displayed in Fig. 8.

As it can be seen, areas that have the best attributes (higher grades) are almost independent of changes in the weights associated with selected decision criteria, which means that the results are solid.

4. Conclusions

This work presented a new siting multi-criteria evaluation methodology combining AHP with GIS. Some criteria are of general use, while others represent specific features of the region under study, which makes this a flexible methodology applicable to any region provided that the specific local conditions are taken into account. Its innovative feature is the two-scale approach, global and local, used to account for inter-municipal interactions and to the inexistence of an initial small set of candidate sites.

The global scale procedure applied to Santiago Island, Cape Verde, revealed the municipality of Praia as the most appropriate one for the erection of a MSWIP, according to the selected criteria (socio-economic, technical and environmental issues, with weights respectively, of 48%, 41% and 11%).
Next, a detailed suitability ranking was performed locally within the Praia municipality by combining the non-environmental feasibility (with a weight of 75%) with the environmental assessment of the plant operation impact (with a weight of 25%). The results obtained revealed a very small set of different possible locations for the MSWIP in the Praia municipality.

The sensitivity analysis performed, six scenarios split into 18 combinations (each scenario had three different combinations), produced encouraging results demonstrating that the ranking scheme is reliable as it indicated that the highly ranked areas remained the most suitable despite the criteria weights variations. In fact, for Scenario 2 for example, the results for all three combinations exhibited a similar trend confirming their strength.

The methodology outlined in the present work can be used as an efficient spatial decision supporting tool to provide politicians, planners and decision makers with important, reliable and objective information for the assessment process of land suitability for siting a MSWIP based on technical, economic, social and environmental criteria.

References

