Methodology for locating regional landfills using multi-criteria decision analysis techniques

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Abstract: In Latin American and Caribbean countries, many landfills are nearing the end of the life cycle. The expectations of multiple stakeholders (the community, the government, non-governmental entities, among others) generate greater complexity to the problem of locating new sites. Decisions on the location of these landfills require the consideration of numerous criteria that must be evaluated simultaneously as a whole. The main objective of this research is to propose a methodology to identify the best locations for regional landfills. Through the literature review, seven (7) criteria have been defined that cover the environmental, social and financial needs of this decision type. Within framework of a selected region with 20 municipalities, approximately 1,200,000 inhabitants and an annual generation of 233,000 tons of waste, 5 possible sites were found that were analyzed under two multi-criteria methodologies: analytical hierarchy process (AHP) and the technique to order the preference for similarity with the ideal solution (TOPSIS). Preference for combination of possible sites was one of the main results. This may allow the rulers to design different strategies to make agreements with the communities involved near these new sites. Likewise, through a sensitivity analysis it was possible to verify the importance that the modification of fares (transport and disposal) may have on the result, converting an alternative as the best, without having been it at the beginning. This research is expected to be a planning tool for local governments that allows them to think about the future of their regions.

Subjects: Environmental Sciences; Environment & Resources; Conservation - Environment Studies; Research Methods in Environmental Studies; Environmental Change & Pollution

Keywords: location; multi-criteria decision analysis; regional landfills; developing countries

1. Introduction

When the goal promoting sustainability, decision-making is never simple. The goal of sustainable development is to reconcile economic growth, social progress and sustainable use of natural resources, maintaining an ecological balance and ensure favourable living conditions now and in the future.
the future. In addition, this decision type must consider the subjectivity of the decision-maker and participation of multiple stakeholders as an essential element for making successful decisions. (Zanghelini et al., 2018).

Currently, management of municipal solid waste MSW is a great challenge for local officials and municipal planners, due to industrialization, population growth and the limited resources of nations, including developed countries that may still have figures more than 20% of MSW sent to landfill (Sauve & Van Acker, 2020).

Although much research is focused today on energy recovery and recycling of valuable materials to reduce loads (Rehman et al., 2020), landfills remain an inseparable part of solid waste management. For a long time, the landfill has been used as a management strategy in many parts of the world and especially in most developing countries (Behrooznia et al., 2018).

Selecting an inappropriate site for a landfill, can bring different negative consequences in different aspects as the environmental, social, and economic impacts, among others. In most developing countries, current methods of site selection depend mainly on evaluation by professional experience or political interests that do not obey scientific objectives (Wang et al., 2018).

Regional solutions for proper management of MSW allow municipalities to partner up into regions and thereby benefit from economies of scale and better application of regulations. A regionally shared landfill, nevertheless, poses challenges from standpoints such as social impacts, environmental risks, and social justice (Hoornweg & Bhada-Tata, 2012).

Regional landfills in developing countries is a very important issue. As elsewhere in the world, there has been a transition from small uncontrolled dumpsites to newer regional landfills that incorporate the latest technologies and provide service with greater coverage. These modern landfills should be carefully located, and their operation should be appropriately controlled (Kamdara et al., 2019).

During previous 30 years, various multi-criteria methods have been used extensively in locating facilities of integrated solid waste management (ISWM) systems. Multi-criteria decision analysis (MCDA) is a generic term applied to methods that help in decision-making and in using personal preferences in cases of conflicting criteria, such as siting of regional landfills. The objective is to assist decision-makers in selecting and ranking alternatives among a finite set based on two or more criteria affecting the final decision and have been adequately evaluated. This process reduces the possibility that stakeholders will regret a decision after it has been made (Barfod, 2012).

The various methods presented in the literature are intended to help decision-makers develop satisfactory solutions. In general, similar procedures are used in these methods: comparing alternatives based on certain criteria, aggregating this information, and evaluating the strength of the evidence in favour of or against the selection of one alternative over others. This process is not as simple as merely identifying which method makes more sense and leads to a better solution, particularly because each method may be based on a certain, distinct rationale. These methods should be thought of as heuristic procedures that generally yield reasonable results in multi-criteria decision problems of great complexity and importance (Romero, 1996).

Since Huang et al. (2011) reviewed the use of MCDA in environmental problems related to solid waste management, it is clear that the analytical hierarchy process/analytical network process (AHP/ANP) is the most widely used method to model this type of situation. While the technique to order the preference for similarity with the ideal solution (TOPSIS) had not yet been applied to this type of problem.

Authors such as Rezaieisabzevar et al. (2020) have shown that site selection methods for landfills, with an emphasis on multi-criteria decision making (multi-criteria decision analysis), have been widely used before and now. The evaluations indicate that the most used methods have been
the weighted linear combination (WLC) and the common and fuzzy analytical hierarchy process (AHP) (F-AHP). Proximity to surface water, nearby settlements, and urbanization, as well as proximity to culturally protected sites, may be among the most used factors in selecting a site.

As Rahimi et al. (2020) demonstrates, the integration of Geographic Information Systems with multi-criteria decision analysis is another strong point when defining sites for landfills. This intersection has been practiced for almost a decade, but it is not study object of this research.

The technique of ordering by similar preferences (TOPSIS) proposed by Hwang & Yoon in 1981 has seldom been applied to selecting locations of regional landfills. This technique compares a set of alternatives by assigning weighting factors to each dimension, normalizing the scores in each dimension, and calculating the differences between the scores of each alternative and the best and worst alternatives in each dimension, thereby generating a ranking of alternatives (Huang et al., 2011).

This method involves working with the ideal, its anti-ideal or a blend of the two. The concept of the ideal alternative has a long tradition in various scientific fields in that it stems from a hypothesis regarding the underlying rationality of human decision-making. The concept has been widely disseminated, e.g., in fields such as group decisions, to the extent that it has become an operational method. The need in this procedure to identify a vector that allows for weighing the selected criteria makes it easy to integrate this technique (and ensure complementarity) with the AHP (Jahanshahloo et al., 2006).

One of the fundamental aspects of this integration, is defining the criteria to take into account. Based on the work of Manyoma-Velásquez (2015), who identified the most important criteria based on a review of the literature and the opinions of a panel of experts, the multi-criteria evaluation was structured for the selection of the site. To this end, criteria were proposed that were framed in the three fundamental dimensions of the ISWM: environmental effectiveness, social acceptance, and economic accessibility (Marshall & Farahbakhsh, 2013).

The objective of this study is to contribute to decision-making on the location of regional landfills in developing countries. For this, a simple and direct methodology has been proposed that allows government authorities to have control, but in turn, stakeholders can participate in this decision. Using a hybrid methodology (AHP-TOPSIS), the best alternative is selected, and a combination of possible sites is obtained.

Considering the three dimensions of sustainability in this framework of hybrid multi-criteria methodologies is not easily found in the reviewed literature. The environmental effectiveness through the distances, the social acceptance through the number of affected and the economic accessibility through the established fare are differentiating characteristics of this research.

The results show the importance of selecting appropriate decision criteria, choosing an appropriate multiple criteria method, and conducting appropriate sensitivity analyses. It is expected that this work contributes to the decision-making processes of stakeholders, the scientific community, and the solid waste management sector in general.

2. Methodology

Traditionally, multi-criteria decision analysis tends to involve several key stages, which are referred to in the literature as a general procedure. Typically, this process is not highly rational in that each stakeholder possesses interests that prioritize his or her objectives and the value system they employ. Several authors identified the stages in this process, and most descriptions of the process cite similar stages, with minor differences typically involving their ordering and level of detail (Hyde, 2006).

To reach the evaluation of alternatives and the selection of best options is essential to complete two previous steps: i. the definition of political and legal requirements for this type of sites and ii. the identification of potential sites (discrete set). The first is the fundamental phase for plans and
programs to be developed by the different actors and the second phase defines the suitability of each of the possible places; factors such as surface conditions and subsoil, climate and proximity prohibitions, among others, are included in the analysis.

Initially, from an extensive literature review, it was important to define the main criteria for the selection of the final site. The alternatives were evaluated and the best option among them was selected using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Analytic Hierarchy Process (AHP). The steps to be carried out are as follows (Figure 1):

From the previous figure, it can be said that:

1. Build the decision matrix. This refers to m alternatives, Ai, which are evaluated based on n criteria, Cj. It is necessary to have a Wj as weighting factor associated with Cj. This Wj can be evaluated in various ways. In this case, the AHP procedure will be used.

2. Normalize the decision matrix. The values obtained from the relationships between alternatives and criteria do not have the same value for all the criteria. This is why it is necessary to normalize values.

3. Build the weighted normalized decision matrix. It is necessary to obtain the “real value” by multiplying by weight vector found.

4. Identify the ideal positive and negative solutions. This is the set of ideal positive values and the set of ideal negative values, according to weighted and normalized decision matrix.

5. Calculate the distance measurements. It consists of calculating how much each alternative differs in each dimension from the “best” option and from the “worst” option.

6. Calculate the relative proximity to the ideal solution and sort preferences. It comprises calculating the relative proximity (Ri) to the ideal solution. To sort preferences, the closer the value of Ri approaches a value of 1, the higher the priority of the corresponding ith alternative.

7. Sensitivity analysis. A sensitivity analysis is performed to verify the stability in the ordering obtained. The results of the multi-criteria analysis indicate the ranking of the sites of potential regional landfills and its sensitivity to the values assigned to the criteria.

3. Results and discussion

3.1. Selection of criteria

The main criteria identified in reviewed literature for selection of the final site from discrete set defined, were the following:
Exposure time (ET): Total time period in years associated with the facility. This time includes the landfill life cycle and the time period for post-shutdown monitoring considered relevant. It was assumed that the period of post-shutdown monitoring was equal to the period of operation.

Distance to water resources (DWR): Euclidian distance in km from the potential landfill site to rivers, lakes, reservoirs, natural springs, wetlands, and similar water resources.

Distance to urban areas (DUA): Euclidian distance in km to urban settlements.

Distance to non-urban areas (DNUA): Euclidian distance in km to locations of historical or cultural interest, tourist destinations, forest reserves, sensitive animal and plant habitats, and similar locations.

Number of affected persons (NAP): Number of inhabitants that may be affected by the construction of the landfill.

Transportation fare (TF): Value in U.S. dollars of transporting each ton of MSW from the city limit to the potential landfill site. This did not include transport during urban waste collection.

Disposal fare (DF): Value in U.S. dollars of processing each ton for disposal at the potential site. Besides investment rate, this includes investment, operation, closure, and post-closure costs.

These seven criteria are a representation of the three great elements of sustainability. At no time is it intended to exhaust this discussion with these criteria.

### 3.2. Identification of alternatives

To develop the methodology, a study area in southwestern Colombia was selected (Figure 2), consisting of 20 municipalities (different sizes) and having a population of approximately 1,200,000 inhabitants. This population generates, on average, 233,000 tons of MSW per year.

For a better behavioural analysis, five (5) possible sites with different storage capacities were considered (called S). Likewise, the analysis was made for 30 years forward.

Table 1 shows the capacity of each potential site, given in hectares, operational time, and assumed post-closure time.

Similarly, Table 2 shows the population affected by each potential site depending on the radius of influence (R in km) and the corresponding scores assigned to the sites. This is in accordance with country regulations and impact proposal. (Decreto 1784, 2017; Decreto-1077, 2015).
In addition, there are areas of special importance that may be affected by the potential sites; these are also important in selecting a site. Table 3 shows special areas such as cultural and religious heritage sites, forest reserves, and recreational areas.

These tables indicate that sites exhibit very specific conditions. A few sites do not possess sufficient capacity to satisfy the 30-year future demand, which means that the final decision involves selecting one and only one of the potential alternatives based on their combinations and subsequent rankings. For greater clarity from this point on, the alternatives will be named according to their corresponding sites or combinations thereof, as in Table 4.

The combination of sites allows local authorities to negotiate with the neighboring community

### Table 1. General characteristics of potential landfill sites

| Potential Sites | Capacity (ha) | Operational time (years) | Post-closure time (years) |
|-----------------|---------------|--------------------------|--------------------------|
| S1 (North)      | 127           | 30                       | 30                       |
| S2 (Central)    | 127           | 30                       | 30                       |
| S3 (East)       | 63.5          | 15                       | 15                       |
| S4 (West)       | 63.5          | 15                       | 15                       |
| S5 (South)      | 63.5          | 15                       | 15                       |

### Table 2. Populations within various radio of influence

| Potential Sites Km | R1 (1–5) | R2 (5–10) | R3 (10–25) | R4 (25–50) | R5 (>50) |
|-------------------|----------|-----------|------------|------------|----------|
| Impact            | 9        | 7         | 5          | 3          | 1        |
| S1 (North)        | 20,596   | 17,399    | 404,057    | 228,844    | 553,791  |
| S2 (Central)      | 22,023   | 113,147   | 336,035    | 611,775    | 141,705  |
| S3 (East)         | 41,768   | -         | 100,895    | 397,779    | 684,244  |
| S4 (West)         | -        | -         | 318,127    | 387,897    | 518,662  |
| S5 (South)        | -        | 85,410    | 386,923    | 484,629    | 267,724  |

### Table 3. Special areas near the potential landfill sites

| Potential sites | Water resources (WR) | Non-urban areas (NUA) |
|-----------------|----------------------|-----------------------|
| S1 (North)      | Stream               | Cultural heritage site|
| S2 (Central)    | River                | Religious heritage site|
| S3 (East)       | River                | Forest reserve        |
| S4 (West)       | River                | Recreational area     |
| S5 (South)      | River                | Cultural heritage site|

### Table 4. Identification of alternatives

| Alternative | A1 | A2 | A3 | A4 | A5 |
|-------------|----|----|----|----|----|
| Sites       | S1 | S2 | S3 | S4 | S5 |

Manyoma-Velasquez et al., Cogent Engineering (2020), 7: 1776451
https://doi.org/10.1080/23311916.2020.1776451
3.3. Evaluation of alternatives and selection of the best option

3.3.1. Step 1: build the decision matrix

Based on consultations with a panel of experts, a weighting factor (W) was developed to assign importance factors to the group’s preference in each criterion dimension. The panel of experts was made up of people who are in state entities, university, guilds, and landfill operators. The total was 32 participants.

When it is difficult to obtain a group of experts, authors as Pourahmadi et al. (2017) indicate the possibility of developing an alternative method such as the Shannon entropy, that allows determining the relative importance of objectives set.

This assignment was performed using the AHP, and the weighting factors are presented in Table 5, which also shows the values that correspond to the alternatives in each dimension when used to develop the decision matrix.

3.3.2. Step 2: normalize the decision matrix

Table 6 shows normalized matrix.

3.3.3. Step 3: develop the weighted normalized decision matrix

The resulting weighted normalized decision matrix is as follows (Table 7).

3.3.4. Step 4: identify the ideal positive solution and ideal negative solution

It is important to clarify that the various dimensions are assigned weighting factors when selecting the ideal solution. Those corresponding to distance should be the maximum possible values, and those corresponding to criteria of time, dollars and other numerical values should be as low as possible (Table 8).

### Table 5. Decision matrix

|   | ET (years) | DWR (km) | DUA (km) | DNUA (number) | NAP | TF (US$/ton) | DF (US$/ton) |
|---|------------|----------|----------|---------------|-----|--------------|--------------|
| W | 28.25%     | 10.95%   | 7.84%    | 3.80%         | 35.81% | 6.68%       | 6.68%        |
| A1 | 60         | 2.22     | 2.38     | 1.48          | 3,567,763 | 8.50        | 9.00         |
| A2 | 60         | 2.38     | 2.95     | 4.31          | 4,647,448 | 5.20        | 6.25         |
| A3 | 45         | 5.84     | 9.55     | 2.53          | 6,030,960 | 3.35        | 4.50         |
| A4 | 45         | 3.30     | 5.59     | 3.76          | 7,012,070 | 4.73        | 6.72         |
| A5 | 45         | 4.75     | 10.83    | 4.26          | 7,527,089 | 2.75        | 3.55         |

### Table 6. Normalized matrix

|   | W  | ET | DWR | DUA | DNUA | NAP | TF | DF |
|---|----|----|-----|-----|------|-----|----|----|
| n1| A1 | 0.52 | 0.25 | 0.15 | 0.19 | 0.27 | 0.72 | 0.64 |
| n2| A2 | 0.52 | 0.27 | 0.19 | 0.56 | 0.35 | 0.44 | 0.44 |
| n3| A3 | 0.39 | 0.66 | 0.60 | 0.33 | 0.45 | 0.28 | 0.32 |
| n4| A4 | 0.39 | 0.37 | 0.35 | 0.49 | 0.53 | 0.40 | 0.48 |
| n5| A5 | 0.39 | 0.54 | 0.68 | 0.55 | 0.57 | 0.23 | 0.25 |

n represents the normalized value of each alternative in each dimension.
3.3.5. Step 5: calculate the distance-related scores
The idea here is to identify how much each alternative differs from the ideal (positive values) and the anti-ideal (negative values) solutions (Table 9).

3.3.6. Step 6: calculate the relative numerical proximity to the ideal solution, and sort preferences
In accordance with the methodology, when sorting the preferences, the closer the value of $R_i$ is to 1, the greater the priority of the $i$th corresponding alternative. In this case, Alternative 3 is the best option (Table 10) for the location of a regional landfill in the area under study, given that it scores the highest against the criteria considered important in the site selection.

Studies, such as those by Erkut and Moran (1991), who used the AHP; Vego et al. (2008), who used PROMETHEE and GAIA; and Mokhtarian et al. (2014), who used VIKOR, indicate the need to explore various multi-criteria methodologies that take into account the context in which decision making occurs and the requirements of siting a regional landfill. In this study, TOPSIS was used for the same purpose as in the previous studies, as in the study by Ekmekcioğlu et al. (2010), although the latter study considered certain MSW treatment methods.

| Table 7. Weighted normalized matrix |
|-----------------------------------|---|---|---|---|---|---|---|
| ET | DWR | DUA | DNUA | NAP | TF | DF |
| A1 | 0.147 | 0.028 | 0.012 | 0.007 | 0.096 | 0.068 | 0.043 |
| A2 | 0.147 | 0.029 | 0.015 | 0.021 | 0.125 | 0.029 | 0.030 |
| A3 | 0.110 | 0.072 | 0.047 | 0.012 | 0.163 | 0.019 | 0.021 |
| A4 | 0.110 | 0.041 | 0.027 | 0.019 | 0.189 | 0.027 | 0.032 |
| A5 | 0.110 | 0.059 | 0.053 | 0.021 | 0.203 | 0.015 | 0.017 |

| Table 8. Ideal positive and negative solutions |
|-----------------------------------------------|---|---|---|---|---|---|---|
| ET | DWR | DUA | DNUA | NAP | TF | DF |
| A+  | 0.110 | 0.072 | 0.053 | 0.021 | 0.096 | 0.015 | 0.017 |
| A-  | 0.147 | 0.028 | 0.012 | 0.007 | 0.203 | 0.048 | 0.043 |

| Table 9. Distance-related scores |
|----------------------------------|---|---|---|
| d+ | A1 | 0.084 | d- |
| A2 | 0.077 | A2 | 0.082 |
| A3 | 0.067 | A3 | 0.087 |
| A4 | 0.103 | A4 | 0.052 |
| A5 | 0.108 | A5 | 0.077 |

| Table 10. Ranking of alternatives |
|-----------------------------------|---|---|
| Alternatives | Ri | Ranking |
| A1 | 0.560 | 2 |
| A2 | 0.517 | 3 |
| A3 | 0.563 | 1 |
| A4 | 0.334 | 5 |
| A5 | 0.418 | 4 |
3.3.7. Step 7: sensitivity analysis

Assuming that fares are the only criteria that can be affected by better or worse performance, we calculated the dollar amount that would be necessary to reduce (in fare) in alternatives other than Alternative 3 such that they would receive a ranking of 1 (see Table 11).

Alternatives 4 and 5 do not become the preferred alternative even if a value of zero is used for any of the fares. This demonstrates the importance of the weighting of the other criteria, whereby their scores are not the best. If the weighting factors were not assigned different values or were equal, the analysis would yield the following results (see Table 12).

The modified ranking shown above demonstrates the sensitivity of the results to the weighting factors assigned to the selected criteria. In this case of assignment of equal weights, the high ranking of Alternative 5 is clearly due to the lower corresponding fare, in terms of both the waste transportation and the final disposal, although the number of people affected by this alternative is the greatest.

It is important highlight that it is not common to find the interrelation of criteria that has been carried out in this research, and even less in the context of our Latin American and Caribbean countries. There are some examples such as Badilla et al. (2008), whose study area was the metropolitan area of Costa Rica, and Marín et al. (2012), who studied the state of Morelos, Mexico, appear alongside studies by Londoño et al. (2010) and Mejía et al. (2012) of a region in Colombia, which were based on GIS integrations and certain multi-criteria tools.

### Table 11. Fare reduction

| Alternatives | TF | DF |
|--------------|----|----|
| A1           | −0.40 | −0.50 |
| A2           | −4.80 | −6.05 |

### Table 12. Modified ranking of alternatives when considering the same weight for each criterion

| Alternatives | $R_i$ | Ranking |
|--------------|-------|---------|
| A1           | 0.231 | 5       |
| A2           | 0.436 | 4       |
| A3           | 0.726 | 2       |
| A4           | 0.479 | 3       |
| A5           | 0.746 | 1       |

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4. Conclusions

This recent work can serve as a basis for updates that consider sustainability dimensions as study object. In most of the research, greater importance has been given to the relationships between the tools than to the selection of the criteria themselves. For this reason, this study focused more on the criteria in use. Additionally, it is not common that studies involve identifying the relationships between distances to various points (water resources, urban areas, and non-urban areas), the number of potentially affected persons and, in particular, fare of waste disposal service.

The importance of assigning weights to the selected criteria is fundamental for the final selection of possible alternatives. The results may be sensitive to inappropriate weighting factors or poor definitions of the corresponding policies, as observed with the reduction in fares.
The combination of sites is presented as an alternative to satisfy the needs of a regional sanitary landfill. Depending on capacities of these sites, you can have different combinations that allow, in some cases, to handle situations of community acceptability and in other cases reduction in disposal and transportation fees.

**Funding**

The authors received no direct funding for this research.

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**Author statement**

The research line in Solid Waste is of common interest to the two research groups participating in this study, which has been studying the different components of municipal solid waste management, from generation, mainly with a vision of separation at the source and collection selective (to make the exploitation more viable) and of strategies for the use of the organic fraction through technologies such as anaerobic digestion to obtain renewable energy, and the improvement of strategies for the stabilization of sanitary landfills and the selection of sites for final disposal.

**Citation information**

Cite this article as: Methodology for locating regional landfills using multi-criteria decision analysis techniques, Pablo César Manyoma-Velásquez, Carlos Julio Vidal-Holguín & Patricia Torres-Lozada, Cogent Engineering (2020), 7: 1776451.

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