

Integrating GIS and Model-Based Analysis in Facility Location

José F. G. Mendes¹

Department of Civil Engineering, University of Minho, Braga, Portugal

ABSTRACT

The purpose of this paper is to develop an approach for the location of facilities that integrates model-based analysis and GIS functions. The model combines the classical transportation costs minimisation with physical, planning and environmental criteria, standing on six steps: distance minimisation, buffer generation, suitability analysis, alternative sites generation, network completion, and final location-allocation solution. Apart from providing a useful model to support location decisions, the approach suggests a way of improving the available proprietary GIS software.

1 - INTRODUCTION

The classical approach to the facility location problem is the use of optimisation methods, such as location-allocation modelling. These methods are characterised by the definition of an objective function (often the minimisation of the distance travelled from the demand points to the facilities) and a set of constraints, such as the number of facilities to be located. The approach demands finding a solution to this problem that optimises the value of the objective function while, at the same time, not infringing the constraints (Clark, 1990).

A typical criticism to this approach is the difficulty of choosing the objective function. The analyst's inability, in many cases, to select an objective function that captures the essential characteristics of the problem can lead to elegant but useless solutions (Grayson, 1973).

In recent times, with the increasing significance of the environmental issues, the inclusion of environmental criteria in the location process of facilities is inevitable, particularly when the facility involves a significant impact. In addition, the consideration of physical and planning criteria is also usual. This type of analysis is basically different from the one mentioned before (optimisation methods). It demands different analytical capabilities, which can be found in GIS environments.

A good example of a problem that demands both the GIS and the model-based analysis is the location of a landfill facility. The distance from the landfill to the waste production points, weighted by the waste to be transported can be minimised using a location-allocation

¹ Associate Professor

model; the site-generation can be developed through a GIS screening process based in a set of physical, planning and environmental criteria, which results in a map of suitable areas.

The advantages of the integration of GIS and model-based analysis in a decision support context were discussed by Clarke (1990) and Fedra and Reitsma (1990). In the present paper, the objective is to develop an integrated approach relevant in the facility location context.

2 - AN INTEGRATED APPROACH

The approach proposed here consists in a combination of a p-median model to minimise the transportation costs, and a suitability analysis which finds suitable areas to locate the facilities.

The application of the p-median model to the study area, defined by demand points and a road network, results in the identification of the central points. These points are the so-called approximate locations of the facilities, around which buffers are generated to find areas to be submitted to a suitability analysis.

The suitability map is obtained through the use of GIS spatial operators, giving a decision space from which alternative sites can be selected. These sites, located near the central points within the buffer areas, should be connected to the former road network in order to re-evaluate the distances travelled using again the p-median model.

The final location solution is the combination of alternative sites that minimises the total distance, in addition with the correspondent allocation solution.

3 - THE INTEGRATED MODEL

A formal integrated model for the location of facilities, following the conceptual outline given above, is now presented.

The model stands on six steps:

- Distance minimisation
- Buffer generation
- Suitability analysis
- Alternative sites generation
- Network completion
- Final location-allocation solution

Each one of these steps is described in the following sections.

3.1 - Distance minimisation

The approximate location of the facilities to serve demand at a number of locations can be determined by considering travel distances over a road network on which demand points and facilities are located and over which travel must take place. Facility locations can be selected that will minimise travel between the facilities and the demand points.

The road network is described in terms of nodes, links, and the length of those links.

Each link connects two nodes. Nodes are the points at the intersections of two or more links. All demand points are located at nodes on the network. The weight w_i represents the value of the demand point at node i , i. e., the number of trips to or from the facility that are required by i .

This kind of problem is called a location-allocation problem and can be solved by the p -median model. The location problem consists of finding the place j occupied by each of the p facilities in the optimum solution. The corresponding allocation problem is to determinate which central facility is to serve each dispersed place, or demand point. The optimum solution is obtained by allocation to the nearest available facility. Allocation is denoted by the value of x_{ij} (x_{ij} is set to one if facility j serves the demand at i , and zero otherwise).

The p -median model can be written mathematically as follows (Goodchild, 1988): Find x_{ij} , $i=1,n$, $j=1,n$ to:

$$\text{Minimise } \sum_{ij} w_i x_{ij} d_{ij} \quad (1)$$

Subject to:

$$x_{ij} = \{0,1\} \text{ for all pairs } i,j$$

$$x_{ij} \leq x_{ji} \text{ for all pairs } i,j$$

$$\sum_j x_{ij} = 1 \text{ for all } i$$

$$\sum_j x_{jj} = p$$

This first step of the integrated model finds the locations of the central points, which minimise the total distance travelled (Figure 1). These central points can be considered as the approximate locations of the facilities.

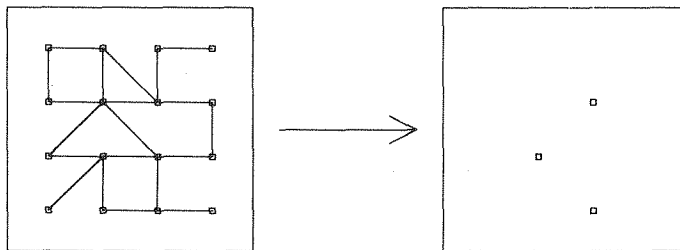


Figure 1 - Road network and central points

3.2 - Buffer generation

In order to find the areas to be submitted to the suitability analysis (next step), buffers should be delimited around the central points found in the previous step.

The main question in this step is to determine the radius of the buffer. It depends essentially on the importance given to the accessibility (distance minimisation) criteria: if it is

very important, then a short radius should be adopted; if not, then the radius may be longer. On the other hand, the dimension of the area obtained by the application of the buffer must be appropriated to the set of criteria adopted for the suitability analysis, which in turn depends on the type of facility to be located. In other words, a very restrictive criteria set applied to a small area could result in an empty or very poor solution (with few alternatives).

As an example, during a landfill facility siting project in Portugal (Silva, 1996), for an area covering a territory of 944 Km² and having 83,425 inhabitants, a radius of 7.5 km was adopted to find an area to be submitted to a screening process.

Figure 2 represents the operation involved in this second step of the model.

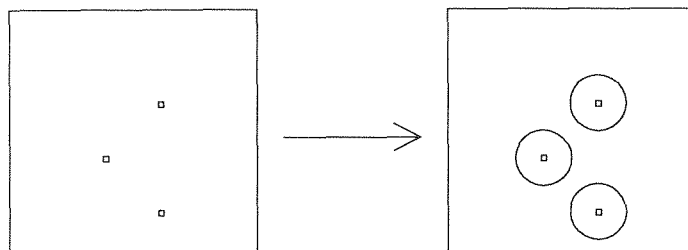


Figure 2 - Central points and buffer areas

3.3 - Suitability analysis

In this step, the buffer areas are submitted to a suitability process in order to create a suitability map through the application of a certain criteria set (Figure 3).

Considering that the analysis at this stage typically involves an area that can be of significant dimension and have heterogeneous physical, environmental and social characteristics, the criteria set should be general, avoiding location requirements that involve the evaluation of field-related criteria. This is because it is impracticable to carry out detailed surveys for the entire study area. Thus, the objective of this step is to reduce the solution space of the problem, using available or easily obtainable information.

The major land suitability mapping approaches have been summarised by Hopkins (1977). The most widely used is the parametric one, in which individual landscape parameters or attributes are separately mapped and rated for suitability, and these ratings are combined into a grand index of suitability (Westman, 1985).

The screening process involved in the suitability analysis should be conducted in a GIS environment, considering the ability of such a system to organise and relate cartographic and alphanumeric data for a given area in order to enable processing, overlay and derivation of thematic maps (Della Bella et al, 1995).

The first task is, obviously, to build the GIS topological database, which should include the relevant information themes derived from the criteria set. The complete conversion process of hard-copy maps into digital GIS databases follows a sequence of three GIS tasks (Mendes, 1995): analogue-to-digital map conversion, topology creation, and attribute assignment. The actual screening process consists in a sequence of spatial analysis operations conducted within the GIS environment. For a full description of the spatial analysis operators, see Goodchild (1991).

Mendes and Silva (1996) present an illustrative example of a general criteria set and the corresponding screening process flowchart for the production of a suitability map for the location of a landfill facility.

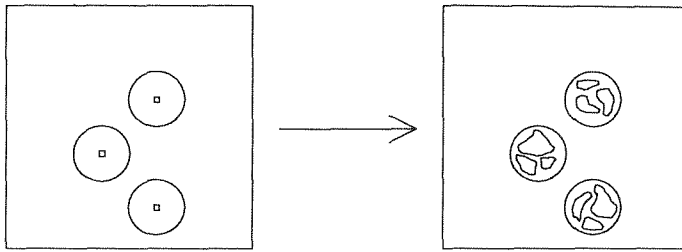


Figure 3 - Buffer areas and suitable areas

3.4 - Alternative sites generation

The suitability map obtained in the previous step is used to generate, for each buffer area, a set of alternative sites for the location of the facilities.

The selected sites should be picked-up from the areas with the highest suitability grand index values. Usually, the choice of the sites must be supported by detailed (and sometimes expensive) field surveys, which are carried out only for the sites under evaluation.

As an example, the location of a landfill facility demands in-situ inspection and evaluation of field-related criteria such as hydrological constraints and soil permeability, among others.

The result of this step can be seen in Figure 4.

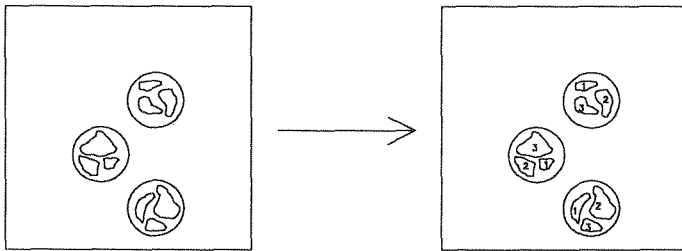


Figure 4 - Suitable areas and alternative sites

3.5 - Network completion

The selected alternative sites are not, in general, coincident with the network nodes. In order to evaluate these sites (next step), links must be added between the sites and the former road network. In practical terms, these links may correspond to existing roads not considered before or to road accesses that would be constructed if the sites are selected for the final

location solution.

The application of this step to a buffer area is presented in Figure 5.

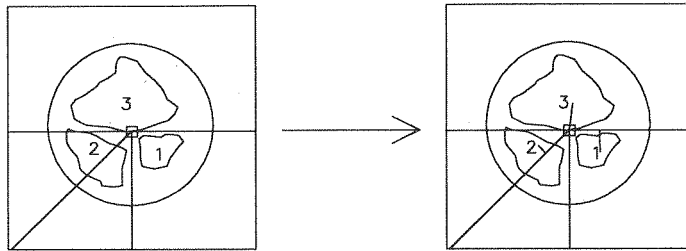


Figure 5 - Alternative sites and new links

3.6 - Final location-allocation solution

The final location for the facilities is the combination of sites, one for each buffer area, that minimises the total distance travelled. For the determination of this final solution, a table must be built which includes the different possible combinations and the distance travelled for each one. Table 1 presents an example, considering three facility units to be selected.

Table 1 - Evaluation of combinations

Site combination	Site for facility unit #1	Site for facility unit #2	Site for facility unit #3	Total distance travelled
1	1	1	1	d_1
2	1	1	2	d_2
3	1	1	3	d_3
4	1	2	1	d_4
5	1	2	2	d_5
6	1	2	3	d_6
7	1	3	1	d_7
8	1	3	2	d_8
9	1	3	3	d_9
10	2	1	1	d_{10}
11	2	1	2	d_{11}
12	2	1	3	d_{12}
13	2	2	1	d_{13}
...

The p-median model can still be used to find the allocation solution and the respective total distance travelled, considering each combination as fixed sites.

The final step can be observed in Figure 6.

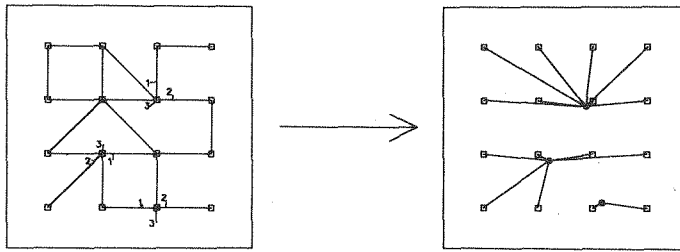


Figure 6 - Completed network and final solution

4 - CONCLUDING REMARKS

In this paper, an integrated approach for the location of facilities was presented. The proposed model combines the transportation costs minimisation with the consideration of physical, planning and environmental criteria. This formulation provides a useful model to assist the decision-makers during location processes. On the other hand, it suggests a way of improving the available proprietary GIS software, which is sometimes accused of being technology-driven rather than (end user) application-driven.

The version considered here includes a p-median model because it is a simple and general model that fits in a great range of facility location problems where the objective is to minimise total travelled distance. The model could be generalised by considering any optimisation model instead of the p-median particular case.

One of the vital aspects of this integrated model is the definition of the buffer radius in step 2, which is selected arbitrarily, depending on the type of facility under study. One way to improve the analysis would be the consideration of different radius, resulting in a kind of sensibility analysis.

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