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AN ANALYTIC HIERARCHY PROCESS MODEL FOR LANDFILL SITE SELECTION

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ABSTRACT

The demand for landfill disposal capacity is presently very high, despite environmental problems often attributed to this disposal technology. Accordingly, the selection of optimal landfill sites presents a major challenge. I propose an analytic hierarchy process-based model for the optimal ranking of potential municipal landfill sites. The AHP approach also allows for inconsistency evaluations of subjective preferences provided by decision makers. The model is applied to the selection of landfill sites in Apulia, a region in southeast Italy. This case study highlights the capabilities of the approach in solving a landfill site selection problem.

INTRODUCTION

The disposal of municipal solid waste (MSW) is one of the major problems facing municipalities the world over. The reduction of the generation rate of waste to be disposed is a major objective both at policy and technical levels. Such an objective can be reached through source reduction and recycling; the remaining waste must be treated by incineration, landfilling, or other disposal technologies. The choice among waste management technologies is complicated by social, organizational, technological, and economic factors. The proportions of MSW disposal capacity taken up by landfill and incineration technologies in several countries are shown in Table 1 [1-4]. As we can see, the percentage of waste disposed of by landfills is always high and often greater than that disposed of by incineration technologies (with or without energy recovery), in spite of claims that incineration poses lower overall risks [5], and in spite of efforts to cut back on the use of landfills in some industrial nations. Perhaps the greatest

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Table 1. Percentage of Waste Disposal Capacity by Landfills, Incineration, or Other Disposal Technologies Adopted in Some Countries

Country	Landfill Disposal Capacity (%)	Incineration Disposal Capacity (%)	Other Disposal Capacity (%)
United States	80	10	10
Japan	21	72	7
Italy	80	15	5
Netherlands	61	14	25
France	36	42	12
Sweden[a]	40	55	5
Hungary	90	9	1

[a] After source recovery.

practical problem in providing adequate landfill disposal capacity is that of finding the safest sites in a way that overcomes or reduces social conflicts and achieves public consensus [6]. This article analyzes the landfill sites selection problem (LSSP) by means of multicriterion decision analysis approach, the analytic hierarchy process [7]. A reference case outlines the capabilities and limitations of the approach followed.

THE LANDFILL SITES SELECTION PROBLEM

The LSSP involves a complex decision-making process carried out by many persons who typically represent distinct albeit related social groups. The process is characterized by a large number of objectives which are often at odds with one another and which depend on many tangible and intangible factors. Tangible factors usually relate to physical and economic variables. When these factors are considered to be prevalent in decision making, quantitative analytic techniques can be used to optimize classical objectives (such as haulage, distances, or operating and fixed disposal costs) by constructing models on the basis of well-known operations research techniques [8, 9]. Such solutions are based on detailed information of relatively low uncertainty. On the other hand, many intangible factors significantly affect both the formulation and solution of an LSSP. Social, political, and environmental factors are typically unquantifiable decision-making variables which are especially important at policy and strategic levels. The information available is characterized by great uncertainty and calls for the use of other analytic tools.

The scientific community has paid wide attention to this class of problem. Environmental decision support systems [10] and knowledge-based locational decision-making systems [11, 12] are information-based locational approaches dealing with site location problems subject to environmental constraints. In More et al. a mixed-integer multicriteria goal programming model is formulated to analyze a waste management program [13]. As far as the LSSP is concerned, a methodology for municipal landfill sites selection is proposed in [14] where environmental, engineering, and economic criteria are amalgamated into a grand index-based scoring system, similar to that adopted in a general facility site location problem [8]. The methodology is applied to the selection of minimum environmental impact sites in the west Athens area. A decision support system is developed to help plan disposal sites in Dar Es Salaam, Tanzania [15]. The system is implemented in a LOTUS 1-2-3 spreadsheet environment that does not require users to have detailed computer skills. A very different and interesting approach is followed in [3]. The approach is based on statistical preferences provided by nearby communities or other state residents for candidate landfill sites and is applied to the case of two landfill sites in Rhode Island, with a view to reducing the level of local opposition to the final site selection.

By looking at general features of an LSSP we observe that its solution implies decision making at strategic, tactical, and operational levels. Such a process is very common in many environmental assessment procedures. The conceptual and normative frameworks of environmental procedures are described by Lee and Walsh at strategic and operational levels in some European and non-European countries [16]. Evaluation processes at the more strategic levels are based on less detailed information and have greater uncertainty than evaluation processes carried out at less strategic levels.

The overall decision-making process requires systemic and integrated institutional procedures as well as appropriate supporting models able to manage quantifiable and unquantifiable variables. The analytic hierarchy process (AHP)-based model developed here is applied to the Apulia region in southeast Italy.

FUNDAMENTALS OF THE ANALYTIC HIERARCHY PROCESS

This section presents the general properties of the AHP. Further details are in [7].

Consider a set of n candidate landfill sites. Suppose some particular decision-making factor makes one landfill site preferable, while other factors make it less preferable. More generally, alternative sites are conflictual with respect to the entire set of decision-making factors usually involved in an LSSP. The use of the AHP requires the identification of the general objective of decision making. The objective is pursued by setting selection criteria consistent with the general objective. Criteria are related to one another one by logical dependencies, jointly having the topology of a tree, schematizing the hierarchy of an AHP. Suppose N is the number of levels in the hierarchy. A hierarchy is structured from the top level ($L = 1$) where the general objective is "located," through intermediate levels $(1 < L < N)$ of decision-making factors or criteria, to the lowest level $(L = N)$ where the n candidate sites are located (Figure 1). A criterion in the hierarchy "governs" the relative sub-criteria at the level immediately below, since the latter affect or contribute to it. Alternatives or criteria are compared with each other with reference to each criterion c in the level immediately above, known as the "governing criterion." A pairwise comparison procedure is adopted for

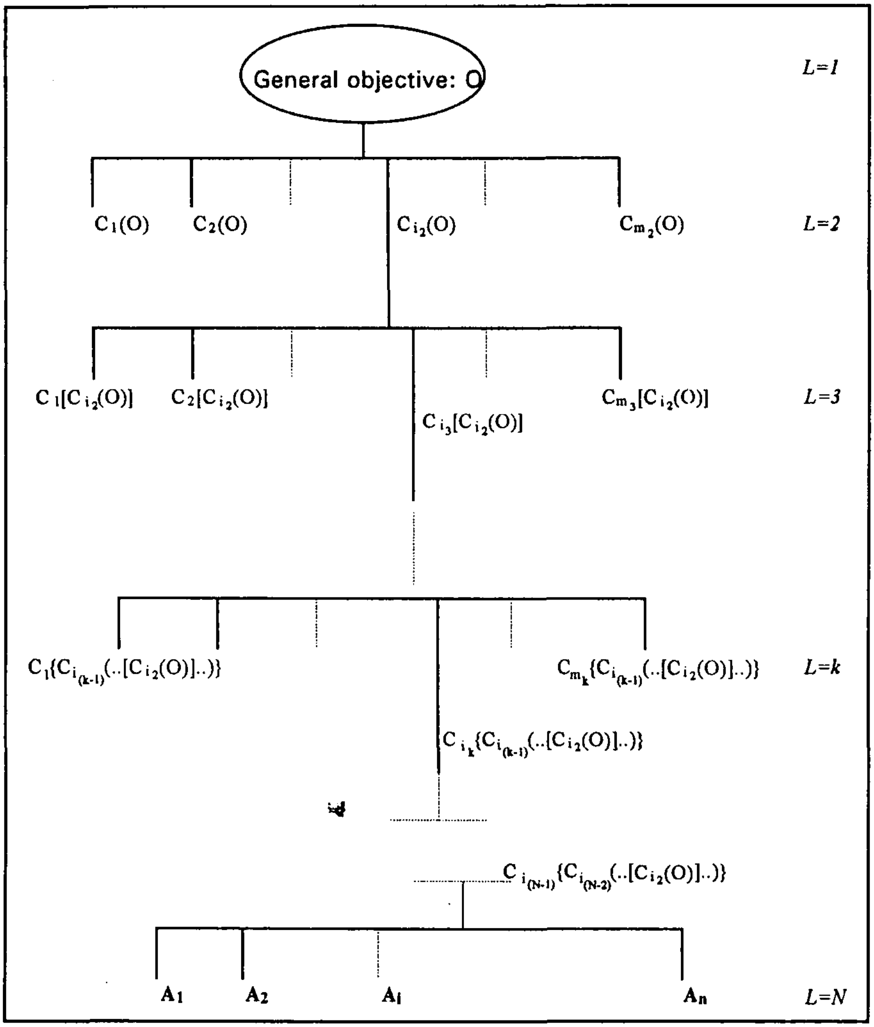

Figure 1. A hierarchy structure of an AHP; $C_{i_k}\left\{C_{i_{(k-1)}}(..[C_{i_2}(O)]..)\right\}$ is the ik-th criterion at the k-level.

each couple of alternatives or criteria, with reference to their relative governing criterion. The set of comparisons constitutes a square dominance matrix.

At the k-th level in the hierarchy ($L = k$), m_k governing criteria and, consequently, m_k square dominance matrices, say $A_{k,c}$, $c = 1,m_k$, are identified. Simplifying the notation shown in Figure 1, we denote **c** as the ik-th governing criterion at the k-th level. Let $n_{k,c}$ be the order of matrix $A_{k,c}$. In pursuing criterion **c** at the (N-1)-th level, element $a(i,j)$ of $A_{N-1,c}$ is a measure of preference or dominance of the i-th alternative compared to the j-th alternative. For $1 < L < (N-1)$ the comparison is made between two sub-objectives (criteria) with reference to the governing criterion in the level immediately above. If $L = 1$ the comparison matrix refers to the first level criterion, the overall objective in the hierarchy.

If judgments relate to tangible factors (e.g., known physical or engineering factors), a decision maker can provide objective evaluations using cardinal scales. On the other hand, if preferences relate to intangible social, political, or environmental factors, a decision maker can provide only subjective estimates according to ordinal scales, ranking qualitative judgments such as "equal importance," "moderate importance," or "absolute importance." In the first case it is easier to gauge the consistency of a decision-maker's judgments. In the case of judgments on intangible factors, consistency may not be ascertainable, particularly when an LSSP is sizeable (high number of alternatives and many decision-making criteria). Consistency is provided by the assumption that

$$(1) \qquad a(i,j) = 1/a(j,i)$$
and
$$a(i,i) = 1.$$

This assumption ensure some important properties in evaluating priorities of items to be ranked. If $n_{k,c} = 2$, relationships (1) ensure consistency between two items compared. If $n_{k,c} > 2$, consistency between two items does not ensure consistency among all items to be ranked, since the transitive consistency property may not be satisfied. Consider, for example, three items, namely i, j, and k. Since $a(i,j) = 1/a(j,i)$ and $a(i,k) = 1/a(k,i)$, then the value $a(j,k)^*$ which is consistent with the previous estimates should be given by $a(j,k)^* = a(j,i)/a(k,i)$. However, a subjective opinion may provide a different estimate on relative dominance between items j and k, i.e., $a(j,k) \neq a(j,k)^*$. In such a case, the best ranking of a set of items which are "governed" by a given criterion **c** at the k-th level can be determined by normalizing the principal eigenvector $W_{k,c}$ obtained by solving the classical eigenvalue/eigenvector problem that in matricial form can be formalized as:

$$(2) \qquad A_{k,c}\, W_{k,c} = \lambda max_{k,c} \cdot W_{k,c}$$

where $\lambda max_{k,c}$ is the principal eigenvalue of $A_{k,c}$, $\lambda max_{k,c} \geq n_{k,c}$. $W_{k,c}$ is the vector of local priorities of items which depend on governing criterion **c** at the k-th level of the hierarchy. By local we mean that $W_{k,c}$ refers to criterion **c** and not to all the criteria of the hierarchy.

By solving problem (2), a $\lambda max_{k,c}$-based inconsistency measure of decision-maker judgments can be evaluated as:

$$(3) \qquad CI_{k,c} = (\lambda max_{k,c} - n_{k,c})/(n_{k,c} - 1), \qquad n_{k,c} \geq 2$$

Index $CI_{k,c}$ and the vector of local priority $\mathbf{W}_{k,c}$ can be calculated for each criterion of the hierarchy. If $\lambda max_{k,c} = n_{k,c}$, judgments are perfectly consistent ($CI_{k,c} = 0$) and the normalized values of elements (the sum of values equal to 1) of a $\mathbf{A}_{k,c}$ column represent the relative importance of the items to be ranked. If $\lambda max_{k,c} > n_{k,c}$, then judgments are not consistent with each other ($CI_{k,c} > 0$). Higher values of $CI_{k,c}$ outline higher degree of inconsistency of a decision-making process. In case of $n_{k,c} = 2$, consistency relationships (1) ensure $\lambda max_{k,c} = n_{k,c}$, and, consequently, $CI_{k,c} = 0$.

A very interesting inconsistency measure can be determined by assigning random values to the elements a(i,j) of each matrix $\mathbf{A}_{k,c}$. The relative random inconsistency index $\mathbf{CR}_{k,c}$ can also be evaluated by eq. (3), where $\lambda max_{k,c}$ is the principal eigenvalue of randomly generated $\mathbf{A}_{k,c}$. $\mathbf{CR}_{k,c}$ represents a limit performance obtained from a set of estimates which are perfectly inconsistent and is the maximum value of $\mathbf{CI}_{k,c}$. It follows that the inconsistency ratio $r_{k,c} = \mathbf{CI}_{k,c} / \mathbf{CR}_{k,c}$ assumes values in the range [0,1] and measures the effectiveness of an evaluation process with reference to a limit measure of perfect inconsistency ($r_{k,c} = 1$ outlines a situation of perfect inconsistency in the estimation process).

The inconsistency ratio can be evaluated also with reference to the overall hierarchy as:

$$(4) \qquad r = \frac{\sum_{L-1}^{N-1} \sum_{c=1}^{m_L} (CI_{L,c} \cdot W_{L,c})}{\sum_{L=1}^{N-1} \sum_{c=1}^{m_L} (CR_{L,c} \cdot W_{L,c})}$$

where $w_{L,c}$ is the generic element of the normalized vector $\mathbf{W}_{L,c}$. Elements $a(i,j) \in \mathbf{A}_{k,c}$ can be provided by attempts to determine an inconsistency ratio of the overall hierarchy that is considered satisfactory (e.g., $r_{max} = 10\%$) according to decision-making objectives.

The Hierarchical Composition Procedure

Proceeding from the lowest to the top level, it is possible to evaluate $\mathbf{W}$, the global priority vector of the hierarchy, by a "composition" procedure. In fact, the set of local priority vectors at the lowest level, $\{\mathbf{W}_{(N-1),c},\ c = [1, m_{(N-1)}]\}$, constitutes a new matrix, namely composite matrix, $\mathbf{CA}_{(N-2),c}$, which refers to criterion c at the (N-2)-th level. Multiplying $\mathbf{CA}_{(N-2),c}$ by the local priority vector,

$\mathbf{W}_{(N-2),c}$, a "composite" priority vector, $\mathbf{CW}_{(N-2),c}$, is obtained. The set of $\mathbf{CW}_{(N-2),c}$ constitutes a new composite matrix $\mathbf{CA}_{(N-3),c}$ that again allows the hierarchical composition procedure in the level above. The procedure is applied recursively up to the first level of the hierarchy where the global priority vector, $\mathbf{W} = \mathbf{CW}_{1,1}$, is obtained. This refers to the unique general criterion of the hierarchy at the first level and represents the final ranking of alternatives.

A sensitivity analysis can be performed to assess the allowable range of each $a(i,j) = \in A_{k,c}$ that does not change the final ranking W. Sensitivity analyses can be usefully performed with reference to estimates at the higher levels in the hierarchy, where subjectivity in the estimates is greater than that at the lower levels. From the top level, through intermediate levels, to the lowest level of the hierarchy, the evaluation process involves strategic, tactical, and operational decision making which draw together in an overall integrated system, according to peculiarities of an LSSP.

AN ANALYTIC HIERARCHY PROCESS-BASED MODEL FOR LANDFILL SITES SELECTION IN APULIA

General Features of Apulia and the Apulian MSW Disposal Regional Plan

The morphology of Apulian territory is characterized by a large number of quarries (with capacities ranging from 10,000 m^3 to 5,000,000 m^3), a result of uncontrolled mining activities in the past. As early as the 1970s, $25 \cdot 10^6$ tons per year of litic material were mined in Apulia. The calcareous rocks and tufa stones mined from quarries did not encourage the recovery of these areas for farming purposes or for irrigation reservoirs. Surface water streams or superficial water tables are mainly confined to small areas which are concentrated in the Tavoliere plain, with rare exceptions in the Provinces of Brindisi and Taranto. The environmental features of Apulia, and a public aversion to the disposal of waste using incinerator technologies, have persuaded decision makers to make strategic choices with the aim of establishing a policy of territorial planning to identify the most appropriate sites for the location of MSW landfills.

Article 52 of Regional Law 24, Protection and Use of Water Resources and Water Reclamation in Apulia, establishes that preferences should be given to the most degraded mining areas in the selection of landfill areas. Regional Law 37 dictates the introduction of mandatory environmental recovery programs to be implemented during and after landfill operation. Both laws were enacted in 1985. In 1988, a first "Program for the Disposal of Municipal Solid Waste produced in Apulia" was prepared. The program was updated by the 1992 "Regional plan for the disposal of Municipal Solid Waste" [17], prepared by a technical regional committee. In this plan, a "first-intervention project" and a "medium-term project" were drawn up. The former envisages the identification of possible landfill sites for every district of the region. The use of sanitary landfills is limited to waste which cannot be recycled, recovered, or disposed of in other ways. However, the estimates for landfill capacity requirements contained in the regional plan are still high (about $17 \cdot 10^6$ m^3), while the current available disposal capacity has been estimated as equal to $3 \cdot 10^6$ m^3 with a net required capacity of approximately $14 \cdot 10^6$ m^3. Such a situation outlines the need for an adequate "expert" tool able to support choices of landfill sites in Apulia.

The Model

In this section we formalize the problem of MSW landfill sites selection on the basis of the AHP previously described. The resulting decision model is tested to investigate the optimal ranking of landfill sites in Apulia. We assume that optimality in searching for ranking mainly relates to environmental concerns, even if further tangible and intangible factors, which jointly affect decision making, could be considered. The extent of the analysis depends on the purposes of the analysis and on the information available. Our source of information in applying the AHP is the regional plan [17], which lays out the criteria that should support decision making in landfill sites selection and details the technical and environmental features of candidate sites. We will consider a sub-set of potential Apulian landfill sites identified in the plan since the aim of this article is to outline the effectiveness of the AHP in an LSSP; the reduction in size of the problem does not affect the validity of the approach adopted.

The structure of the hierarchy that we propose to tackle the problem is shown in Figure 2. The hierarchy has four levels (N = 4). The top level is represented by the overall objective of decision making which consists of the optimal ranking of a given set of MSW landfill sites in order to minimize their total environmental impact (as in [14]). At the lowest level (L = 4) is located the set of candidate landfill sites. We consider twenty-six alternatives almost equally distributed over the five districts of Apulia. The second level is constituted by seven environmental components which we assume are the most significantly involved during a landfill operation. The set of attributes which characterize each environmental component is located at the third level. Attributes of different environmental components are generally different in number and character.

Subjective opinions at the second and at the third level are provided according to the qualitative scale of relative importance shown in Table 2 and already suggested in [7]. Evaluations to rank the twenty-six alternatives at the fourth level with reference to each criterion at the third level are provided according to the cardinal scales in Table 3. The scales have been obtained by modifying the ones suggested in [18] on the basis of the detailed information about each site provided by the Regional plan. The sixteen selection criteria in Table 3 refer to environmental features which may characterize each site. The other eleven criteria relate to landfill technical and management requirements. We assume that engineering

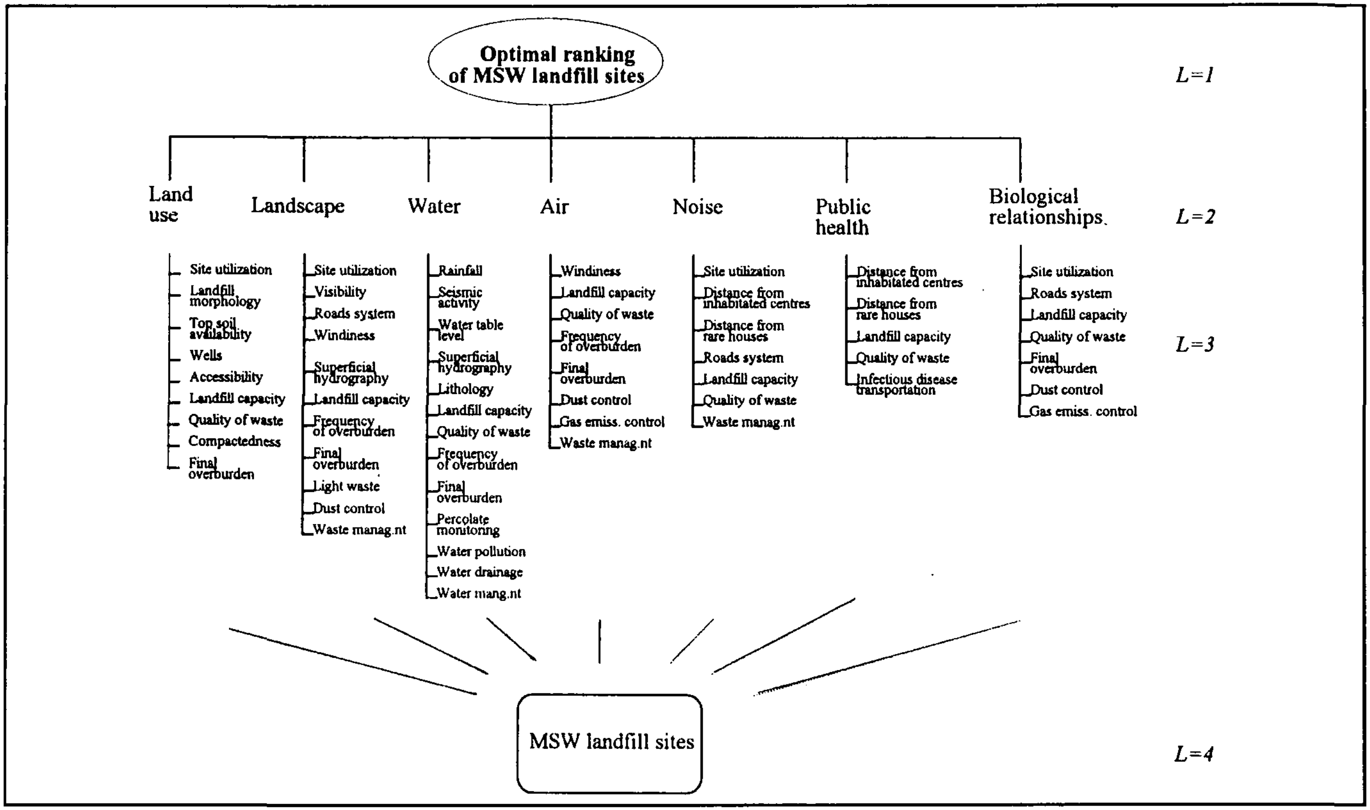

Figure 2. A hierarchy structure to select MSW landfill sites by AHP.

requirements are equally fulfilled by all the candidate sites. As one can observe, the estimates at the second and third levels may be affected by greater uncertainty than the evaluations of engineering features of landfill sites which are located at the fourth level. Nevertheless, the final ranking of candidate landfill sites will be affected by the entire set of estimates provided.

DEVELOPING THE APULIA CASE: ESTIMATES, RESULTS, AND COMMENTS

According to the purposes of the present article, we provide subjective and objective evaluations for factors at each level of the hierarchy proposed in Figure 2. All subjective preferences are given by numerical values which are the elements of each comparison matrix. The number of preferences for each dominance matrix, $A_{k,c}$, is $n_{k,c} \cdot (n_{k,c} - 1)/2$, since the consistency relationships (1) have to be considered. Table 4 shows the comparison matrix, $A_{1,1}$, whose elements are measures of subjective preferences attributed to the environmental components at the second level in the ranking process of landfill sites. Preferences are provided according to the preference scale of Table 2.

By solving the eigenvalue-eigenvector problem based on $A_{1,1}$, we calculate the eigenvector, $W_{1,1}$, of local priorities of the environmental components and the

Table 2. Scale of Relative Importance [7]

Intensity of Relative Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate importance of one over another	Experience and judgment slightly favor one element over another.
5	Essential or strong	Experience and judgments strongly favor one activity over another.
7	Very strong importance	An element is strongly fravored and its dominance is demonstrated in practice.
9	Absolute importance	The evidence favoring one element over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between two adjacent judgments.	When compromise is needed.
Reciprocals of above non-zero numbers	If element i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared to i.	

relative principal eigenvalue, $\lambda_{\max 1,1} = 7.932$. As we can see, $\lambda_{\max 1,1}$ is greater than the order of the comparison matrix $A_{1,1}$ ($n_{1,1} = 7$), so the estimates that we provide are not perfectly consistent. The inconsistency index is $CI_{1,1} = 0.155$. By assigning random estimates to the $7 \cdot (7-1)/2$ elements of $A_{1,1}$, we evaluate the random inconsistency index $CR_{1,1} = 1.32$ [see also 7] and the relative inconsistency ratio $r_{1,1} = 0.118$. This value is a measure of the degree of inconsistency which is about 12 percent of the limit inconsistency randomly generated. Such an evaluation process is performed for each governing criterion of the hierarchy.

Table 5 shows the local priority vectors, $W_{2,c}$, $c = 1,...7$, the corresponding principal eigenvalues $\lambda_{\max 2,c}$, the inconsistency indices $CI_{2,c}$, the random inconsistency indices $CR_{2,c}$, and the inconsistency ratios $r_{2,c}$, of the criteria at the third level, which are compared with each other with reference to each environmental component at the second level of the hierarchy. Because of limited space, comparison matrices $A_{2,c}$, $c = 1,...,7$, one for each of the seven environmental components are not shown in this article. Matrices $A_{2,c}$ have different order (see Table 5) ranging from 5 (5 factors at the 3rd level relate to the "Public health" component) to 13 (13 factors for the "Water" component).

At the fourth level in the hierarchy there are twenty-six candidate landfill sites. They have to be compared with each other with reference to each of the twenty-seven distinct governing criteria at the third level (see Figure 2). Each comparison matrix has the same order ($n_{3,c} = 26$). Table 6 shows the nine distinct local priority vectors, $W_{3,c}$, $c = 1,...,9$, which refer to the first nine governing criteria of the third level (see Figure 2). The governing criteria depend on the "Land use" environmental component, the first governing criterion at the second level. The set of eigenvectors $W_{3,c}$, $c = 1,...,9$, constitutes the composite dominance matrix $CA_{2,1}$. As can be seen, the values of the elements in the last three columns in the matrix are equal to the reciprocal value of the number of candidate sites (1/26) since no preferences among sites are expressed with reference to the last three governing criteria of the first nine at the third level. The criteria relate to engineering and operative technical requirements which we assume to be equally fulfilled by all the alternatives. All the eigenvalues are equal to the number of alternatives compared ($\lambda_{\max 3,c} = 26$, $c = 1,...,27$), since the cardinal scale in Table 3 is adopted to assign preferences; consequently, all inconsistency indices are equal to zero.

By multiplying each matrix $CA_{2,c}$ by local priorities $W_{2,c}$ of corresponding governing criteria at the second level, we find the composite priority vectors, $CW_{2,c}$, $c = 1,...,7$, as shown in Table 7. Each composite priority vector represents the ranking of candidate landfill sites with reference to its corresponding criterion at the second level. For example, by multiplying matrix $CA_{2,1}$ (Table 6) by the local priority vector $W_{2,1}$ (1st column of Table 5) we determine the composite priority vector $CW_{2,1}$ of landfill sites with reference to the first governing criterion at the second level ("Land use" environmental component).

The set of vectors $CW_{2,c}$ constitutes a new composite matrix, $CA_{1,1}$. Finally, by multiplying this matrix by the vector of the local priorities of the environmental

Table 3. Cardinal Scales for Sixteen Selection Criteria at the Third Level of the Hierarchy in Figure 2 (Adaptation from [18])

Site Selection Criteria	Situation	Magnitude of the Impact
Site utilization	Suburbs	10
	Rough ground	8 ÷ 9
	Operating quarry	5 ÷ 7
	Exhausted quarry	2 ÷ 4
	Marshland	1
Landfill morphology	Level area	7 ÷ 8
	Not level area	4 ÷ 6
	Quarries and ravine	1 ÷ 3
Visibility	Visible from inhab. centres	7 ÷ 9
	Visible from main roads	4 ÷ 6
	Not visible	1 ÷ 3
Distance from inhabited centers	< 500 m	10
	500 ÷ 1000 m	5 ÷ 8
	1000 ÷ 2000 m	2 ÷ 5
	> 2000 m	1 ÷ 2
Distance from rare houses	< 500 m	10
	500 ÷ 1000 m	5 ÷ 8
	1000 ÷ 2000 m	2 ÷ 5
	> 2000 m	1 ÷ 2
Roads system	Heavy urban traffic	8 ÷ 10
	Heavy extra-urban traffic	4 ÷ 8
	Roads of industrial areas	2 ÷ 4
	Not heavy traffic	1 ÷ 2
Rainfall (annual average)	>1200 mm	9 ÷ 10
	1000 ÷ 1200 mm	7 ÷ 9
	700 ÷ 1000 mm	5 ÷ 7
	< 700 mm	2 ÷ 5
Windiness	High windiness area	6 ÷ 8
	Low windiness area	2 ÷ 5

Table 3. (Cont'd.)

Site Selection Criteria	Situation	Magnitude of the Impact
Seismic activity	1 class area	10
	2 class area	7
	3 class area	3
	Not seismic area	1
Maximum water table level from landfill	<2 m from waste	10
	2 ÷ 10 m	7 ÷ 9
	10 ÷ 20 m	4 ÷ 7
	> 20 m	1 ÷ 4
Lithology	High fractured calcareous	9
	Low fractured calcareous	8
	High fractured "calcareniti"	7
	Low fractured "calcareniti"	6
	Sand and scree	5
	Marls	4
	Clay	3
	Alluvial deposits	1 ÷ 2
Superficial hydrography	Near lakes and rivers	8 ÷ 10
	Water body polluted by percolate	4 ÷ 8
	Far from superficial water bodies	1 ÷ 3
Wells position	Downstream	6 ÷ 10
	Upstreams	1 ÷ 6
Top soil	Not available	8 ÷ 10
	Available near operating quarries	4 ÷ 6
	Available "in situ"	1 ÷ 3
Accessibility	Absent	7 ÷ 10
	Not asphalted road without maintenance	6
	Not asphalted road with casual maint.	4
	Not asphalted road with periodic maint.	3
	Asphalted road with casual maint.	2
	Asphalted road with periodic maint.	1
Landfill capacity	> 5,000,000 m^3	7 ÷ 10
	2,000,000 ÷ 5,000,000 m^3	3 ÷ 7
	< 2,000,000 m^3	1 ÷ 3

Table 4. Comparison Matrix, $\mathbf{A}_{1,1}$, and Local Priority Vector, $\mathbf{W}_{1,1}$, of the Seven Environmental Components. Preferences Refer to the General Objective of the Hierarchy and are Provided on the Basis of the Preference Scale in Table 2.

Environmental Component	C1	C2	C3	C4	C5	C6	C7	$W_{1,1}$
C1: Land use	1.00	5.00	3.00	3.00	4.00	0.14	0.20	0.113
C2: Landscape	0.20	1.00	0.20	0.20	0.33	0.11	0.20	0.023
C3: Water	0.33	5.00	1.00	1.00	3.00	0.17	0.25	0.067
C4: Air	0.33	5.00	1.00	1.00	3.00	0.17	0.25	0.067
C5: Noise	0.25	3.00	0.33	0.33	1.00	0.17	0.20	0.038
C6: Public health	7.00	9.00	6.00	6.00	6.00	1.00	6.00	0.478
C6: Biol. relation.	5.00	5.00	4.00	4.00	5.00	0.17	1.00	0.214

$\lambda max_{1,1} = 7.932$
$CI_{1,1} = 0.155$
$CR_{1,1} = 1.32$
$r_{1,1} = 0.118$

Table 5. Local Priority Vectors, $W_{2,c}$, Principal Eigenvalues, $\lambda max_{2,c}$ Inconsistency Indices, $CI_{2,c}$, Random Inconsistency Indices, $CR_{2,c}$, and Inconsistency Ratio $r_{2,c}$ of the Criteria at the Third Level, Which are Compared with Each Other with Reference to Each Governing Criterion (Environmental Component) at the Second Level in the Hierarchy (see Figure 2). Comparison Matrices are Evaluated According to the Preference Scale of Table 2.

	Local Priority Vectors, $W_{2,c}$, $c = 1,\ldots,7$						
	Land Use	Landscape	Water	Air	Noise	Pub. H.	Biol. Rel.
	$W_{2.1}$	$W_{2.2}$	$W_{2.3}$	$W_{2.4}$	$W_{2.5}$	$W_{2.6}$	$W_{2.7}$
	0.240	0.020	0.079	0.236	0.069	0.300	0.080
	0.048	0.193	0.017	0.101	0.410	0.172	0.034
	0.078	0.033	0.175	0.145	0.099	0.271	0.439
	0.307	0.141	0.127	0.062	0.112	0.131	0.165
	0.031	0.034	0.099	0.030	0.237	0.126	0.049
	0.152	0.119	0.073	0.200	0.037		0.096
	0.035	0.095	0.144	0.200	0.035		0.136
	0.020	0.024	0.039	0.026			
	0.089	0.160	0.014				
		0.163	0.081				
		0.018	0.021				
			0.120				
			0.009				
$\lambda max_{2,c}$	10.656	12.376	15.943	8.637	7.902	5.261	7.370
$CI_{2,c}$	0.207	0.138	0.245	0.091	0.150	0.065	0.062
$CR_{2,c}$	1.434	1.486	1.543	1.351	1.322	1.058	1.322
$r_{2,c}$	0.144	0.093	0.159	0.067	0.114	0.062	0.047

Table 6. Local Priority Vectors of the Twenty-Six Landfill Sites[a]

	Local Priority Vectors, $W_{3,c}$, c=1,..,9								
	Site Utilization	Landfill Morphology	Top Soil Availability	Wells	Accessibility	Landfill Capacity	Quality of Waste	Compacted-ness	Final Overburden
Site Number	$W_{3,1}$	$W_{3,2}$	$W_{3,3}$	$W_{3,4}$	$W_{3,5}$	$W_{3,6}$	$W_{3,7}$	$W_{3,8}$	$W_{3,9}$
1	0.039	0.043	0.043	0.009	0.029	0.026	0.038	0.038	0.038
2	0.039	0.043	0.043	0.060	0.059	0.052	0.038	0.038	0.038
3	0.039	0.043	0.043	0.020	0.015	0.026	0.038	0.038	0.038
4	0.026	0.043	0.043	0.060	0.059	0.026	0.038	0.038	0.038
5	0.026	0.043	0.043	0.060	0.029	0.052	0.038	0.038	0.038
6	0.039	0.043	0.043	0.060	0.020	0.026	0.038	0.038	0.038
7	0.039	0.043	0.043	0.060	0.059	0.017	0.038	0.038	0.038
8	0.052	0.043	0.043	0.012	0.012	0.052	0.038	0.038	0.038
9	0.052	0.043	0.043	0.007	0.010	0.052	0.038	0.038	0.038
10	0.019	0.021	0.011	0.060	0.010	0.052	0.038	0.038	0.038
11	0.078	0.043	0.011	0.012	0.059	0.052	0.038	0.038	0.038
12	0.039	0.043	0.043	0.008	0.015	0.052	0.038	0.038	0.038
13	0.019	0.014	0.043	0.030	0.029	0.052	0.038	0.038	0.038
14	0.031	0.043	0.043	0.015	0.029	0.052	0.038	0.038	0.038
15	0.039	0.043	0.043	0.060	0.059	0.052	0.038	0.038	0.038
16	0.039	0.043	0.043	0.060	0.059	0.052	0.038	0.038	0.038
17	0.039	0.043	0.043	0.060	0.059	0.026	0.038	0.038	0.038
18	0.039	0.043	0.043	0.060	0.015	0.052	0.038	0.038	0.038
19	0.039	0.043	0.043	0.060	0.015	0.052	0.038	0.038	0.038
20	0.026	0.043	0.043	0.012	0.059	0.026	0.038	0.038	0.038
21	0.078	0.043	0.043	0.020	0.059	0.052	0.038	0.038	0.038
22	0.031	0.043	0.043	0.020	0.059	0.017	0.038	0.038	0.038
23	0.022	0.043	0.043	0.030	0.059	0.009	0.038	0.038	0.038
24	0.078	0.043	0.043	0.060	0.059	0.005	0.038	0.038	0.038
25	0.017	0.014	0.011	0.060	0.010	0.007	0.038	0.038	0.038
26	0.019	0.011	0.011	0.020	0.059	0.052	0.038	0.038	0.038

[a] Each vector refers to the corresponding governing criterion of the third level depending on the first governing criterion of the second level (the environmental component "Land use").

Table 7. Composite Priority Vectors of the Candidate Landfill Sites for Each Governing Criterion at the Second Level in the Hierarchy:
The Set of **CW**$_{2,c}$, c=1,...,7, Constitutes the Composite Matrix **CA**$_{1,1}$

	Composite Priority Vectors, **CW**$_{2,c}$, c = 1,..,7						
	Land Use	Landscape	Water	Air	Noise	Public Health	Biology Related
Site Number	**CW**$_{2,1}$	**CW**$_{2,2}$	**CW**$_{2,3}$	**CW**$_{2,4}$	**CW**$_{2,5}$	**CW**$_{2,6}$	**CW**$_{2,7}$
1	0.028	0.033	0.041	0.039	0.033	0.035	0.033
2	0.049	0.039	0.038	0.037	0.041	0.040	0.044
3	0.031	0.036	0.042	0.034	0.035	0.036	0.033
4	0.042	0.031	0.041	0.035	0.027	0.034	0.032
5	0.045	0.041	0.034	0.037	0.056	0.053	0.046
6	0.043	0.037	0.040	0.035	0.037	0.036	0.034
7	0.043	0.035	0.041	0.034	0.041	0.049	0.029
8	0.035	0.042	0.039	0.042	0.039	0.038	0.044
9	0.034	0.040	0.039	0.039	0.039	0.037	0.044
10	0.039	0.039	0.039	0.042	0.030	0.031	0.043
11	0.041	0.043	0.032	0.042	0.047	0.038	0.046
12	0.031	0.044	0.038	0.042	0.047	0.037	0.046
13	0.032	0.044	0.044	0.047	0.049	0.053	0.043
14	0.032	0.039	0.045	0.036	0.043	0.038	0.045
15	0.049	0.047	0.033	0.047	0.038	0.031	0.046
16	0.049	0.042	0.036	0.039	0.040	0.035	0.046
17	0.045	0.039	0.033	0.039	0.043	0.050	0.033
18	0.047	0.039	0.045	0.035	0.043	0.039	0.045
19	0.047	0.042	0.036	0.042	0.039	0.039	0.044
20	0.027	0.040	0.037	0.039	0.031	0.034	0.034
21	0.046	0.040	0.039	0.037	0.046	0.044	0.045
22	0.029	0.031	0.041	0.036	0.016	0.024	0.029
23	0.029	0.030	0.031	0.033	0.033	0.033	0.026
24	0.051	0.037	0.041	0.037	0.031	0.032	0.024
25	0.031	0.036	0.040	0.037	0.036	0.047	0.022
26	0.028	0.034	0.035	0.037	0.040	0.037	0.042

Table 8. Ordinal Ranking of Candidate MSW Landfill Sites

Ordinal Ranking of Landfill Sites	Hierarchy Priority Vector	Site Number
I	0.048	5
II	0.047	13
III	0.044	21
IV	0.043	17
V	0.042	7
VI	0.041	18
VII	0.041	2
VIII	0.041	19
IX	0.041	11
X	0.040	16
XI	0.039	8
XII	0.039	12
XIII	0.039	14
XIV	0.039	9
XV	0.038	25
XVI	0.038	15
XVII	0.037	26
XVIII	0.036	6
XIX	0.036	10
XX	0.035	4
XXI	0.035	3
XXII	0.034	1
XXIII	0.034	20
XXIV	0.033	24
XXV	0.031	23
XXVI	0.027	22

components (see $\mathbf{W}_{1,1}$ in Table 4) we find the hierarchy priority vector, $\mathbf{W} = \mathbf{C}\mathbf{W}_{1,1}$ which is shown in Table 8 and allows for the ordinal ranking of the twenty-six candidate sites.

The final site selection could be obtained by searching for sites which show higher preferences according to **W**, and are preferable to others also for different factors (e.g., cost or political factors) that are not considered in this article.

The global inconsistency ratio (rel. (4)) is r = 0.071, i.e., the inconsistency of the overall estimation process is about 7 percent of the randomly performed limit estimation process. Such an evaluation points out the high degree of consistency provided by the overall set of estimates. Of course, if in other actual cases a hierarchical structure with more levels is adopted and/or a greater number of

Table 9. Allowable Variability Ranges of the Values of the Comparison Matrix $\mathbf{A}_{1,1}$ Elements: a(i,j) Values within the Allowable Range Do Not Affect the Final Ranking of Candidate Landfill Sites

Element a(i,j) of the Comparison Matrix $\mathbf{A}_{1,1}$	Allowable Variability Range
a(1,2)	3 ÷ 9
a(1,3)	3 ÷ 5
a(1,4)	3 ÷ 4
a(1,5)	3 ÷ 7
a(1,6)	1/8 ÷ 1/6
a(1,7)	1/6 ÷ 1/5
a(2,3)	1/5 ÷ 1/4
a(2,4)	1/9 ÷ 1/3
a(2,5)	1/5 ÷ 1/2
a(2,6)	1/9 ÷ 1/7
a(2,7)	1/5 ÷ 1/3
a(3,4)	1 ÷ 2
a(3,5)	1 ÷ 6
a(3,6)	1/7 ÷ 1/5
a(3,7)	1/4 ÷ 1/2
a(4,5)	1 ÷ 9
a(4,6)	1/9 ÷ 1/2
a(4,7)	1/4 ÷ 1/3
a(5,6)	1/7 ÷ 1/5
a(5,7)	1/9 ÷ 1
a(6,7)	5 ÷ 7

subjective estimates are provided, then a higher value of the inconsistency ratio could be obtained.

Finally, a sensitivity analysis to assess the criticality of subjective estimates on the final ranking has been performed. Table 9 shows the allowable variability ranges of the values of the comparison matrix $A_{1,1}$ elements; a(i,j) values within these ranges do not affect the final landfill sites ranking shown in Table 8. As we can see from sensitivity analysis, estimates may be more or less critical according to whether relative allowable ranges are respectively narrower or wider. For example, the opinion regarding the relative importance between the "Landuse" and "Landscape" environmental component is not critical since the value of the element a(1,2) can vary in a wide range without modifying the final ranking in Table 8. On the contrary, the opinion is critical regarding the relative importance attributed to the "land use" and "air" environmental components (element a(1,4)) or to the "Water" and "Air" environmental components (element a(3,4)).

Results obtained are not absolute but relative since they depend on the subjective estimates provided and on the formulation proposed in the worked case. Other technical, political, and social factors as well as another structure of the hierarchy could have been considered. Complexity of decision making may require that the set of judgments and the problem formulation be provided by a selected group of experts.

COMPUTATIONAL DETAILS

Actual sizes of LSSPs usually involve many candidate sites and selecting criteria. In the worked case developed in the present article there are twenty-six alternatives and thirty-five governing selecting criteria (including the overall objective of the hierarchy). For each governing criterion an eigenvector/eigenvalue problem has to be solved to evaluate the corresponding local priority vector and inconsistency indices. The hierarchical composition procedure is then applied to evaluate the final ranking of alternatives. Initial estimates often have to be updated when unsatisfactory local and/or global inconsistency measures are evaluated. Moreover, sensitivity analysis on $A_{k,c}$ elements requires several further iterations of the overall evaluation procedure required by AHP.

Even if the theoretical background of the AHP is not particularly complex, its computational complexity drives the need for a computer program to support the overall decision-making process by updating estimates. In the worked case of the present article, a computer program was coded in Quick Basic language. Results were obtained after a few seconds for each set of evaluations relating to a governing criterion. The evaluation of a random inconsistency index is obtained by simulating random estimates for each comparison matrix in the hierarchy and solving the relative eigenvalue/eigenvector problem for each run of the simulation. If the number of simulations and the size of a comparison matrix increase then computational time increases as well. However, given that a random inconsistency index depends only on the order of the corresponding comparison matrix, the index is evaluated once and does not change during the updating process of subjective opinions. Generally speaking, times required to formulate problems and provide satisfactory consistent estimates are greater than automatic computing times.

SUMMARY AND CONCLUSIONS

Notwithstanding the varied technical and environmental recommendations provided by scientists, technicians, and waste management plants in several countries, MSW landfilling is still a widely adopted disposal option. At present, no evident reasons can be found to make a different trend foreseeable.

Accordingly, greater attention should be paid to meeting landfill disposal capacity requirements. A major challenge in this regard is the problem of landfill site selection, largely due to strong and widespread public aversion; the merits of landfills are debated at policy and technical and scientific levels. We believe that an integrated, systemic approach can be helpful. In this article, I have proposed an analytic hierarchy process-based model to cope with the complexity of landfill site selection problems. The model is effective for ranking alternatives and for helping to gauge the degree of consistency of the overall set of subjective opinions. The model has been applied to a worked case, the optimal selection of candidate landfill sites in Apulia, using a subjective hierarchy structure. The worked case is based on a subjective structure of the subjective initial preferences.

Further research is required to investigate the effect of new possible hierarchical structures and other preference ordinal scales in evaluating LSSPs. The approach suggested also could be considered in cases in which statistical preferences of nearby communities are available [see 3]. Such investigations could help address and perhaps resolve the public consensus conflicts that characterize LSSPs.

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