Development of a Landfill Model to Prioritize Design and Operating Objectives

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ABSTRACT

The application of scientifically based decision making tools to help address solid waste management issues dates back to the early 1960's. Researchers continue to use operations research tools to help optimize landfill design and operating parameters. This paper discusses the application of another type of decision making tool, the analytical hierarchy process (AHP), to address priority ranking for a number of landfill engineering design and operating objectives in developing and developed countries. .In this application, the AHP is used to rank, and prioritize, economic, environmental, health and safety, legislative and public perception objectives for landfill design and operations specific to landfill distance from a community, and precipitation levels. Results from a global survey using the Delphi process is included, with a discussion on the survey's impact on the objective rankings relative to community proximity and precipitation. The Delphi process worked extremely well, and was an excellent tool to use in this application. The initial results from the objective rankings show promise in the development of an integrated model for landfill design and operation.
Keywords: analytical hierarchy process, solid waste, landfill disposal, operations, design, delphi process, operations research, sustainability, integration

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1. INTRODUCTION

Until recently, open dumping was the most common form of disposal of municipal solid waste (MSW) in population centers throughout North America, and many parts of the world (Bolton, 1995). However, within the last thirty years, a significant shift has occurred towards adopting sophisticated and technologically sound approaches MSW disposal on land. Recently, landfilling of MSW has taken on a new complexity with the emergence of bioreactor landfilling as a preferred method for managing solid waste (Reinhart and Townsend, 1998). As these developments occur, it becomes readily apparent that the infrastructure required to operate and maintain these new types of landfills is becoming quite challenging, notwithstanding the fact that the more space the infrastructure consumes within a landfill, the less space there is for landfilling, and consequently, a reduced landfill capacity (Ljung, 2001).

In recent times, the practice of using sophisticated decision making tools for MSW management has increased considerably (Everett and Modak, 1996; Revelle *et al*., 1997; Edgecombe, 1999; Chandrakanthi *et al.*, 2002). However, an aspect, which all these applications share besides the use of operational research (OR) tools, is the lack of weighting in the parameter application. For example, in route selection for MSW collection, priority ranking of certain route parameters over others was not addressed (Gottinger, 1988). As well, the larger impacts that involve environmental, financial, and public perception were generally not considered in the Gottinger’s type of analysis, nor were they ranked in terms of priority relative to one another.

Consequently, this paper discusses the use of the analytical hierarchy process (AHP) to address relative priority issues related to landfill design and operation In this analysis, an AHP model is presented to prioritize landfill objectives. The end result is a four-level hierarchical layout in AHP, which can evaluate landfill objectives, covering objectives and numerous landfill design and operational parameters.

2. THEORETICAL BACKGROUND

Over the last twenty–five years or so, a number of approaches have been developed to rank, evaluate, and prioritize parameters mathematically and subjectively. The parameters can be quantified by numerical ranking of importance (ie. 1 is less than 2 for example) or ranked subjectively depending on a number of sociological factors that could be very difficult to quantify (Lahlou, 1991; Zeiss, 1995). Several decision making approaches are available for application in the environmental field including: Matrix Method (Rau & Wooten, 1980; Lahlou, 1991),the Analytical Hierarchy Process (AHP) (Saaty, 1977) and Step Matrix Method (Zeiss, 1995). The Matrix Method has been used in a number of decision making scenarios to address environmental impacts of transportation projects and urban development (Rau and Wooten, 1980). The AHP has seen extensive use in a number of decision making scenarios, including politics, finance, and performance indicators to name a few, but not particularly popular in the environmental field (Varis, 1989, Lahlou, 1991, Zeiss, 1995). The Step Matrix Method has found applications in landfill siting exercises (City of Red Deer, 1994). In the current study, the Analytical Hierarchy Process was selected as the most appropriate tool for evaluating landfill objectives, and ultimately landfill components such as leachate collection systems,. It has been used in prior landfill applications by Siddiqui et al., (1996).

The AHP uses a four step approach to solve a decision making problem (Saaty, 1977). A decision hierarchy is created by breaking down the decision problem into a hierarchy of interrelated decision elements. Input data is then collected by pair wise comparisons of decision elements. The "eigenvalue" method is used to estimate the relative weights of decision elements. The relative weights of decision elements are then aggregated to arrive at a set of ratings for the decision alternatives.

This system, as proposed by Saaty (1977), develops priorities in hierarchical structures, and has been extensively used in a number of decision making scenarios, including energy policy development and allocations of resources, material handling and purchasing, manpower selection and performance measurement, project selection, and nuclear site selection. Although the scenarios where AHP have been applied are quite diverse, and appear unrelated, they all share some common features (Zahedi, 1986). All these scenarios involve the following; they are decision problems, they involve rating decision alternatives for evaluation, selection, or prediction, and they involve some qualitative as opposed to quantitative elements that play an essential role in the problem. Most cases are also quite complex in that they involve a host of interrelated elements with varying degrees of impact on the decision.

To set up an AHP to evaluate and rank alternatives, the problem elements must be structured into a hierarchy of levels of detail. At each level, the elements are broken down into components, which constitute the level below. The first level is the overall goal,, the second level is the objective , and the third level is typically the alternative plan of action that impacts the overall objective. The advantages of applying AHP process are summarized in Figure 1. Conversely, it is also important to understand that AHP is not without its problems. Several problems are discussed below.

The Hierarchy of Decision: When the hierarchy is incomplete (ie., when all elements of one level are not related to all those above them in the hierarchy), one may get counterintuitive composite weights. As well, no theoretical framework exists for modeling decision problems into a hierarchy.

Input Data: In AHP, the data collection on pairwise weights is based on the premise that the evaluator is inconsistent in expressing his or her preferences. Consequently, once the desired level of consistency is achieved through consistency checks, no errors will exist in the input data. However, were the data considered as observations with random errors, the random errors may not be eliminated by consistency checks.

Estimation of Relative Weights: Various criteria are suggested for the selection of an estimation method, and there appears to be no consensus on the choice of estimator. The The eigenvalue method is an estimation method used in conjunction with AHP has a long history of use and has the support of a software product on the market. (Zahedi , 1986).

Aggregation of Relative Weights of Various Levels into Composite Relative Weights: Since composite weights constitute the final outcome of AHP, the statistical and rank-preserving properties inherent in the estimation of relative weights also has an effect on the composite weights.

3. PROBLEM DEFINITION

As evident from literature and a review of current practices, landfill design and operation is typically conducted in a piece-meal basis not accounting for the full utilization of resources, or the full potential design and operational impact that may occur within a landfill environment. There are a number of reasons for this situation ranging from the advent of new technology and approaches to dealing with landfills in general, to the range of expertise required in applying the technology. For example, it may be necessary to solicit the expertise of geotechnical practitioners for landfill liner design, and mechanical and electrical engineers for dealing with landfill gas collection, treatment and energy generation issues.

To resolve this situation, a fundamental shift in approach needs to be taken by considering the landfill as a single unit rather than a number of components with little or no perceptive relation to each other. The landfill operation encompasses five fundamental criteria (or termed objectives during the AHP analysis) that determine landfill's operational success: financial, environmental, health and safety, public perception and legislative. These criteria are frequently cited in literature as aspects that need to be considered when selecting a site for the landfill, or evaluating a landfill facility which can have a potentially negative impact on the environment (Rau and Wooten, 1985, Kärmann, 2000) . They are briefly described here.

Financial: A budget is required for design, construction, operation, maintenance, and to address the long term liability of a landfill. Inherent to this issue is the fact that landfill operators in developed countries must be able to continue to finance technological changes in their landfill design and operation, and support post-closure care monitoring. Consequently, the financial demands on landfill owners and operators, and revenue changes over time can have a significant impact.

Environmental: Landfills have the potential to contaminate groundwater, and be contributors to global greenhouse gas budget through the generation of methane and carbon dioxide. Aside from aesthetic and day-to-day operational concerns, these two issues are of paramount importance when owning and operating a landfill for MSW disposal. These impacts also weigh very heavily in the post-closure care of a landfill, and also in helping to identify the post-closure use of a landfill site.

Health and Safety: As with the environmental aspect, landfills are equally a concern from a public health aspect. An example of this would be the practice of scavenging, commonly practiced in most developing countries. In much of the developed world scavenging is restricted , if not prohibited, because of health and safety concerns such as being cut by broken glass or metal, or by being around heavy equipment . Fatalities continue to occur even in developed countries, particularly in the case of waste collection system operators (Patterson, 2004),. Community safety concerns related to landfill traffic are also an ongoing issue, particularly when a landfill is close to the community it services. From a road safety perspective, garbage trucks traveling through a community have been cited as a major reason for re-locating a landfill site (City of Calgary, 1992).

Public Perception: As a result of many of the factors identified above, this criteria is also an issue since landfills are typically viewed as a potential health, environmental, and financial liability, regardless of the level of due diligence applied to operating the facility. In the eyes of the majority of the public, landfills are still largely viewed as a nuisance, although it is recognized as a necessary one.

Legislative: Throughout the last two decades, there has been a considerable amount of legislation generated, predominantly in the developed world to address environmental and health concerns associated with landfills. However, the legislation can have a constraining effect on landfill design and operating components if innovation is suppressed by the nature of the legislation itself (Tchobanoglous *et al.*, 1993).

Considering these facts, in the current application of AHP, a number of landfill design and operational parameters have been identified that require prioritization and ranking. Some of the parameters are financial related (ie. capital and operating costs), and others relate directly to environmental matters (e.g. efficiency of a leachate collection system). Since landfill design and operating scenarios continue to evolve, the parameters chosen focus on landfill financial and capacity components, landfill liner design and leachate collection, and landfill gas generation and extraction.

4. LANDFILL DESIGN AND OPERATION.

A sanitary landfill for the disposal of MSW is a public service facility. The most important function of a properly designed and operated landfill is to provide safe containment for waste. To protect the environment, modern sanitary landfills are subject to various legislation. Landfills may also need to meet additional requirements established by the owner, operator, or legislative authorities. (Bolton, 1995).

Landfills are typically designed to contain the type of waste disposed in them. Consequently, the more hazardous the waste, the more stringent the design criteria will be. Landfills, which are expected to contain hazardous waste materials, are designed with much more rigour than those containing waste of a non-hazardous nature. Surprisingly, this approach has only been undertaken within the last two decades or so, and only because of legislation, principally driven by the United States Environmental Protection Agency, or USEPA (McBean *et al.*, 1995). Public concerns and perceptions about groundwater and soil contamination were the typical drivers behind these changes in approach. Until the advent of bioreactor landfill practices in late 1990s, typical landfill design criteria focused on landfill liner and leachate collection systems, with some emphasis on gas collection systems. As a result of some of these new developments, landfills have become challenging to design, and more sophisticated in their mode of operation The type of landfill design and operation considered in this application was one which could apply to some of the developing and developed world. Some jurisdictions have moved beyond the descriptions provided below, and some have yet to achieve this basic design and operational level.

Operationally, waste material is typically transported to a landfill site, either privately or by a publicly owned vehicle. Once on landfill property, the vehicle is usually scaled in (ie. weighed) and a ticket is issued (usually for private vehicles) by the scale operator or, the weight and vehicle is recorded automatically in the scale. Depending on the operation, the vehicle then drives off to dispose of its material. The waste disposal occurs at the landfill working face, or at a designated waste drop-off area.

In the latter instance, the waste would then need to be transported to the landfill working face by a larger disposal vehicle. This practice has become common at the more sophisticated and developed landfill sites, to minimize safety concerns. At the landfill working face, a number of landfill operating scenarios take place. The material is screened either visually or in many cases physically by a traffic controller and other field staff. If the material is deemed acceptable, it is placed in the tipping face of a landfill cell, compacted by a large mechanical motorized compaction unit, and eventually covered by a layer of soil or some type of alternate cover material. This alternate cover material can range from snow (typically in the winter time in cold climates) to synthetic materials. Synthetic materials are typically used to either help extend landfill life or when natural cover materials such as soil are not available. The tipping face usually extends to a height of 3 to 4 meters and can typically vary in length from 20 to 100 meters. The width of the working face depends on the traffic flow to the landfill, the amount and type of waste material entering the site, the site conditions, and the topographical constraints of the disposal area.

Landfill daily cells are designed to handle a day's volume of garbage and a minimum amount of soil cover. However, there are some critical components to a daily cell that need to be kept in mind from an operating perspective. For example, landfill cell geometry is selected to create the most effective and efficient landfill daily cell in terms of maximizing volume and minimizing surface area. This approach also helps to minimize vector problems, control traffic, and minimize the impact of fire should it occur. The latter is not to be taken lightly, because for most landfill operators, it is the one issue they do not want to face. Landfill fires can take days, and weeks in some cases, to extinguish, and can consume a large amount of resources in terms of manpower and equipment (Wilson, 2004).

The cell footprints within a landfill should be configured to maximize the life of a landfill and provide a storage capacity of at least a year, and preferably more. This also helps to minimize the cost of having to design and construct cells and to disrupt site disposal operations. Three key drivers for a cell's footprint are topography, weather conditions and quantity of MSW.

Topography will determine the location and in many cases the size of landfill footprint that can be established in an area. Weather conditions, particularly in northern climates, is another critical factor to consider because it helps establish the design and construction schedule of a bottom liner system. Tied into this is the quantity of waste material that will be disposed of in the landfill cell. In cold climates, a compacted clay bottom liner must be covered by solid waste before freeze up to prevent the liner from being exposed to freeze thaw cycles, and which can compromise its integrity.

5. APPLICATION OF THE ANALYTICAL HIERARCHY PROCESS (AHP)

To apply AHP to the process of landfill construction and operation, the five objectives identified above are ranked in order of priority. However, once the objectives are established and ranked, the next step in the process would be the ranking of the landfill sub-objectives and associated parameters In this instance, the landfill construction and operating sub-objectives refer to the larger parts of the landfill infrastructure as follows :

- leachate collection, treatment, and disposal systems,
- landfill final cover,
- stormwater collection, catchment, treatment, and disposal,
- gas extraction and management systems and,
- the overall landfill disposal system itself.

Based on these components, which are also illustrated in Figure 2, the respective parameters for these components could then be selected for evaluation as alternatives. Parameters that could be selected include hydraulic conductivity in the case of leachate collection systems, percent organics in the MSW stream in the case of gas collection, the thickness and type of landfill cover, the design storm and rainfall intensity for stormwater catchment, and the type of landfill disposal system itself, based on waste types targeted for disposal.

6. PROPOSED MODEL AND METHODOLOGY

Figure 2 illustrates the conceptual four level hierarchy model. The goal of this model is to rank in priority landfill design and operating parameters based on the objectives and covering objectives (the second and third levels in the AHP hierarchy). In this context the model would be able to evaluate various alternative scenarios in various parts of the world regardless of geography, climate or level of development, for a particular landfill.

To create some rigour around a landfill scenario and to gather meaningful data, the a comprehensive methodology was developed. The methodology is described in this section.

6.1 Data Collection Methodology

To identify the criteria or objectives for use in the AHP hierarchy, opinions from many landfill design and or operating experts were required. Consequently, a research study was undertaken using the Delphi process to measure certain evaluation criteria to help rank specific landfill design and operating parameters (Crews, 2004). The process itself is an interactive survey tool which enables the interviewer and interviewee to discuss a topic for mutual benefit (Joos et al, 1999). Those experts who volunteered to participate included fifteen from the America's, two from Asia, and one from Europe, for a total of 18 participants. Fourteen of these participants were from countries considered the developed world including the United States, Canada, Sweden, and four were from countries considered the developing world, Columbia, India, Mexico, and Thailand.

The purpose for doing this work was to identify in an integrated fashion the importance of certain landfill design and operating parameters relative to one another. Through this process, a landfill expert, be a landfill designer, operator, or researcher, can use this method to determine what aspects of a landfill facility they should focus their resources and efforts on. The objectives referred to is from the second step in a four step AHP Model shown in Figure 3. This survey focused only on the second step of the hierarchy.

6.1.1 Description of the test landfill

The test landfill consists of the following of infrastructure:

- a leachate management system consisting only of leachate collection and/or re-circulation. Other forms of treatment such as specific leachate treatment facilities are not included to keep the system relatively simple. It is assumed though that the leachate, if not re-circulated, can be safely disposed of down a sanitary sewer.
- a landfill gas generation and collection system. Gas treatment and flaring are not included with this system, again to keep the system relatively simple.
- a storm water management system, an interim and final landfill cover system, and,
- modern landfill disposal practices, including, including compaction requirements.

6.1.2 Community Size and Distance

The landfills considered for analysis serve relatively large urban centers with populations between 500, 000 and 2 million people. This is not to infer that landfills serving smaller centers are less sophisticated in their operation than larger ones. However, it is more likely that the type of infrastructure identified above would occur in a landfill serving a larger population center than a smaller one due to the larger financial capacity that typically exists in larger population centers.

As long as the test landfill has the type of infrastructure identified above, it would be represented in the model. However, it was important to note that the landfill does not include other components such as recycling or composting facilities. Although these may exist on the same site, for simplicity they are not included in the modeling exercise.

For the purposes of the analysis, landfills were classified into three categories, ie. **I** being distance from community <1 km, **II** being distance from community between 1 and 10 kilometres, and **III** being distance from community > 10 kilometres. The landfills would be typically operated as described in Section 4.

6.1.3 Precipitation

The precipitation level was used in the classification system to accommodate the climatic and geographical aspect of the test landfill. High precipitation levels were used for areas such as Bogota, Colombia or Bangkok, Thailand. Low precipitation levels were used for communities in arid to semi-arid regions such as Phoenix, Arizona or Jaipur, India. Medium level precipitation levels were used for communities such as Linköping, Sweden, or Montreal, Canada.

6.1.4 Final Landfill Classifications

Using the AHP , pairwise comparisons were completed for the nine landfill types (see Table 1). An example of the pair wise comparisons is also included. Comparisons were completed with the 18 participants; over the phone in eleven cases, in person five times, and by fax twice. Three of the participants were design engineers, four were academics and the other eleven were owner/operators of landfills. Each participant was completely unaware of the other participants input.

In the AHP, a ranking system, such as the one provided below is often used to help compare criteria or subcriteria to one another. Research in this field indicates that a numerical scale from 1 to 9 generally provides the best results. Consequently, that is the system that has been adopted for this survey.

1. Equal Importance
2.
3. Weak Importance of one over another
4.
5. Essential or strong importance
6.
7. Very strong importance
8.
9. Absolute importance

2,4,6,8 Intermediate values between the two adjacent judgments (Saaty and Vargas,1988)

The data provided by the participants was input into Expert Choice 2000, a commercially available AHP software product based in Virginia, U.S. (Expert Choice, 2004). Priority rankings were then derived from the pair wise comparisons for ranking purposes using Expert Choice 2000. The details of converting the pairwise comparisons to priority rankings are provided in Saaty and Vargas (1988).

7. PRESENTATION AND DISCUSSION OF RESULTS

The results from the survey are provided in Figures 3 a, b, and c, and in Figure 4. The first three data points in each plot of Figure 3 were based on information provided by three landfill design engineers interviewed. The following four data points were from landfill experts affiliated with universities in Canada and Asia. The last eleven data points were from experts who have many years of experience in the landfill operations area in the Americas, and Europe. Figure 4 provides the priority rankings determined statistically using the geometric mean, from the raw data plots. Data points 4, 7, 16 and 17 were from the landfill experts in India, Thailand, Mexico, and Columbia respectively. Based on the landfill design features, and mode of operation mentioned in the paper, all four priority ratings are quite similar to those in the developed world. These conclusions would seem to differ with those studying solid waste management practices in other parts of the developed world (Magpili, 2006, Louiis and Magpili, 2006). However, what became clear in discussing the type of landfill design and operation used in this paper, is that, similar to the developed world, some regions in the developing world, operate more modern landfill facilities than others. For example, Bogata, Columbia, operates a very modern type landfill, even compared to those operating in the U.S. or Canada. Concurrent with that application, other communities of Columbia and Canada, as an example, still operate some of their facilities as dumps.

Nonetheless, it is apparent that, typically, health and safety issues are given the highest priority. An exception to this rule would appear to be from the United States, where legislative pressures create a somewhat different atmosphere for individuals working in the landfill field. Another fact of importance is that many of the landfills in the U.S. are privately owned and/or operated.

From the geometric means, some preliminary conclusions can be made about the data. Health and safety, environment, and public perception stand out, compared to legislative factors and financial aspects in relative priority. In Figure 4, when comparing the various landfill scenarios to one another, it also becomes apparent that priority shifts begin to occur with distance and precipitation. Although health and safety, and environmental concerns remain at the forefront as concerns, the further the landfill is from the community, the greater the focus becomes on the financial aspect, relative to public perception and legislation.

When the distance is more than one kilometre from the nearest community, health and safety, and environmental issues become less of a concern than when the landfill is closer, and financial considerations become more important. This would seem to be quite intuitive, however, while health concerns become less of a priority, it is quite interesting that environmental concerns remain quite consistent as a priority regardless of precipitation levels and distance from the community. There was no clear trend in this area amongst the respondents. Many viewed the environment as quite a high priority irrespective of precipitation level, or distance from the community.

The legislative aspects were predominantly linked to health and safety, and environmental concerns. The closer a landfill was to the local community, the more likelihood there was of exceeding the legislative requirement. The further away a landfill was from the community, the greater the likelihood that the legislative requirements would be met, but not exceeded. Lastly, based on Figure 4, health and safety becomes a slightly higher priority when the climate is drier. Public perception and environment become less of a concern with a drier climate.

8. CONCLUSIONS

The AHP process appears, in concept, to be a good tool for ranking in order of priority landfill design and operating objectives, covering objectives and parameters. This conclusion is based on general criteria of concern found within the literature associated with landfill design and operation. The Delphi process also worked well, although language and telecommunication issues need. For example, telephone and electronic communication worked better in some parts of the world than in others. In one case multiple faxes needed to be sent back and forth, in another, telephone communication suffered a temporary breakdown. Although the third level in the hierarchy seems relatively straight forward, the fourth level could include twenty landfill parameters or more.

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Landfill Type	Precipitation Level	Distance from Community
Ia	High	> 1 kilometre
b	Medium	
c	Low	
IIa	High	1 to 10 kilometres
b	Medium	
c	Low	
IIIa	High	>10 kilometres
b	Medium	
c	Low	

Table I Landfill Classification System

	Finance	Environment	Health and Safety	Legislative	Public Perception
Finance	1	1/4	1/4	1/3	1/4
Environment	4	1	1	2	1
Health	4	1	1	2	1
Legislative	3	1/2	1/2	1	1/2
Public Perception	4	1	1	2	1

Table 2 Pairwise Comparisons

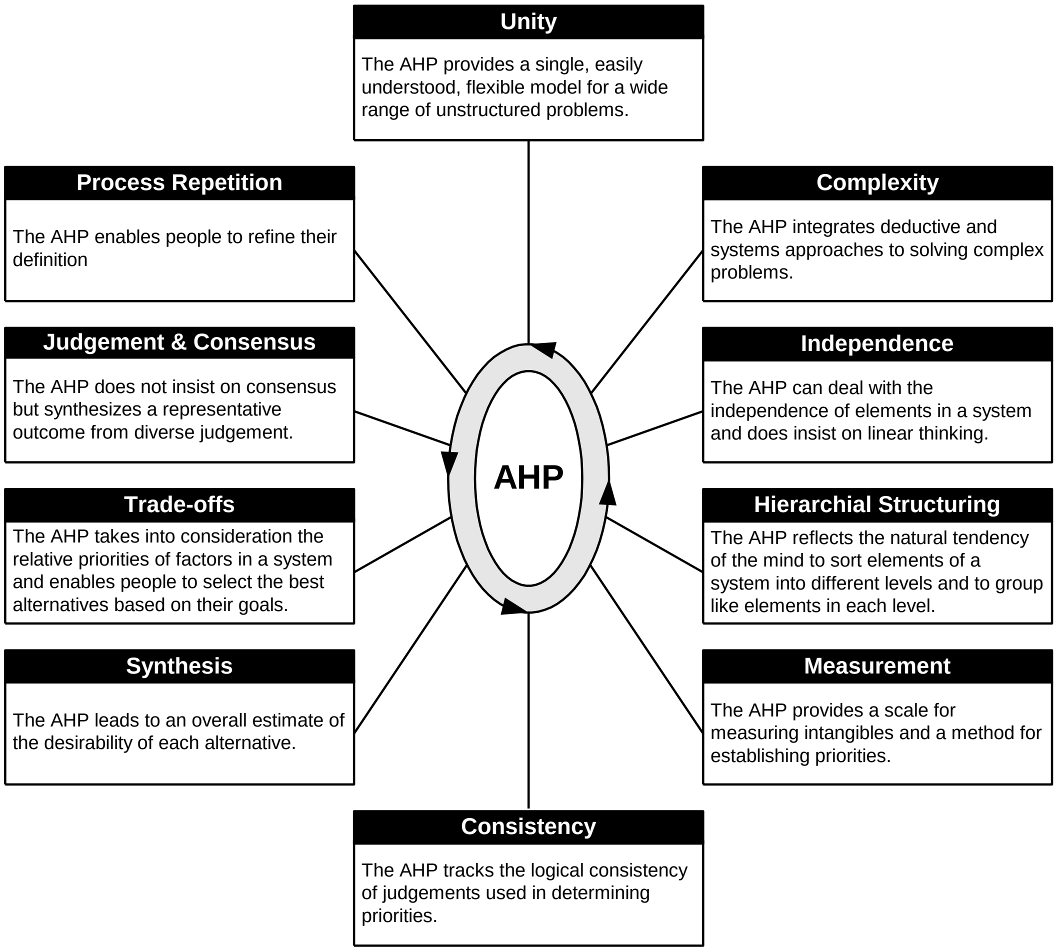

Figure 1. Advantages of AHP (modified from Saaty, 1996, Kazakidis *et al.*, 2003)

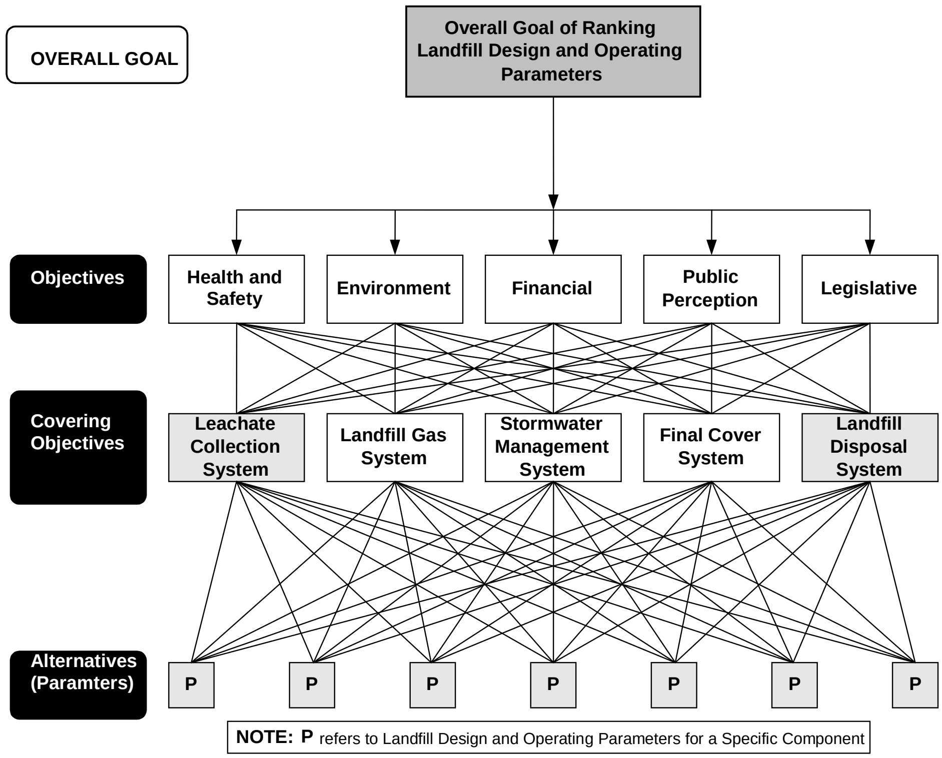

Figure 2. Proposed AHP Hierarchy

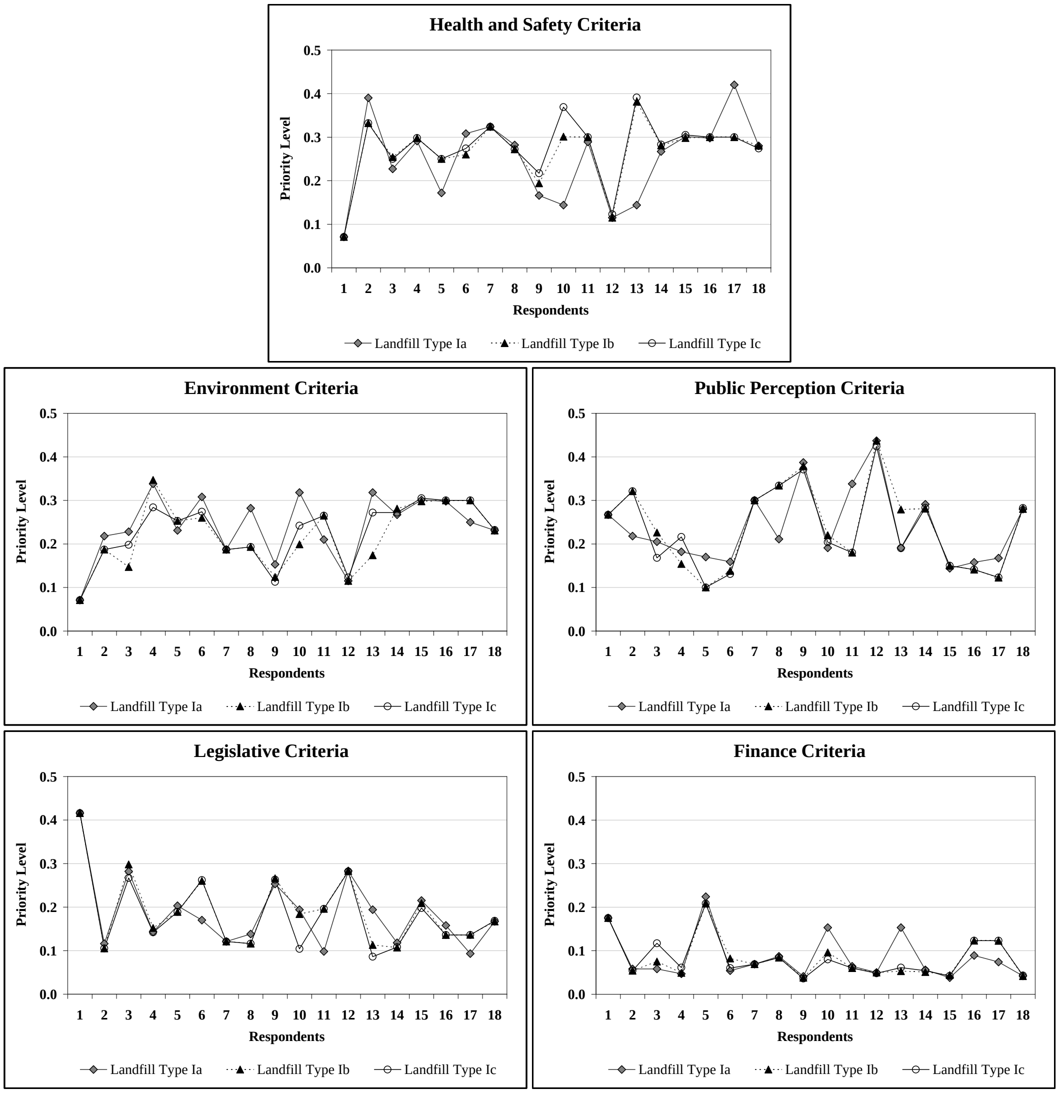

Figure 3a. Survey results (Landfill Type Ia, Ib and Ic)

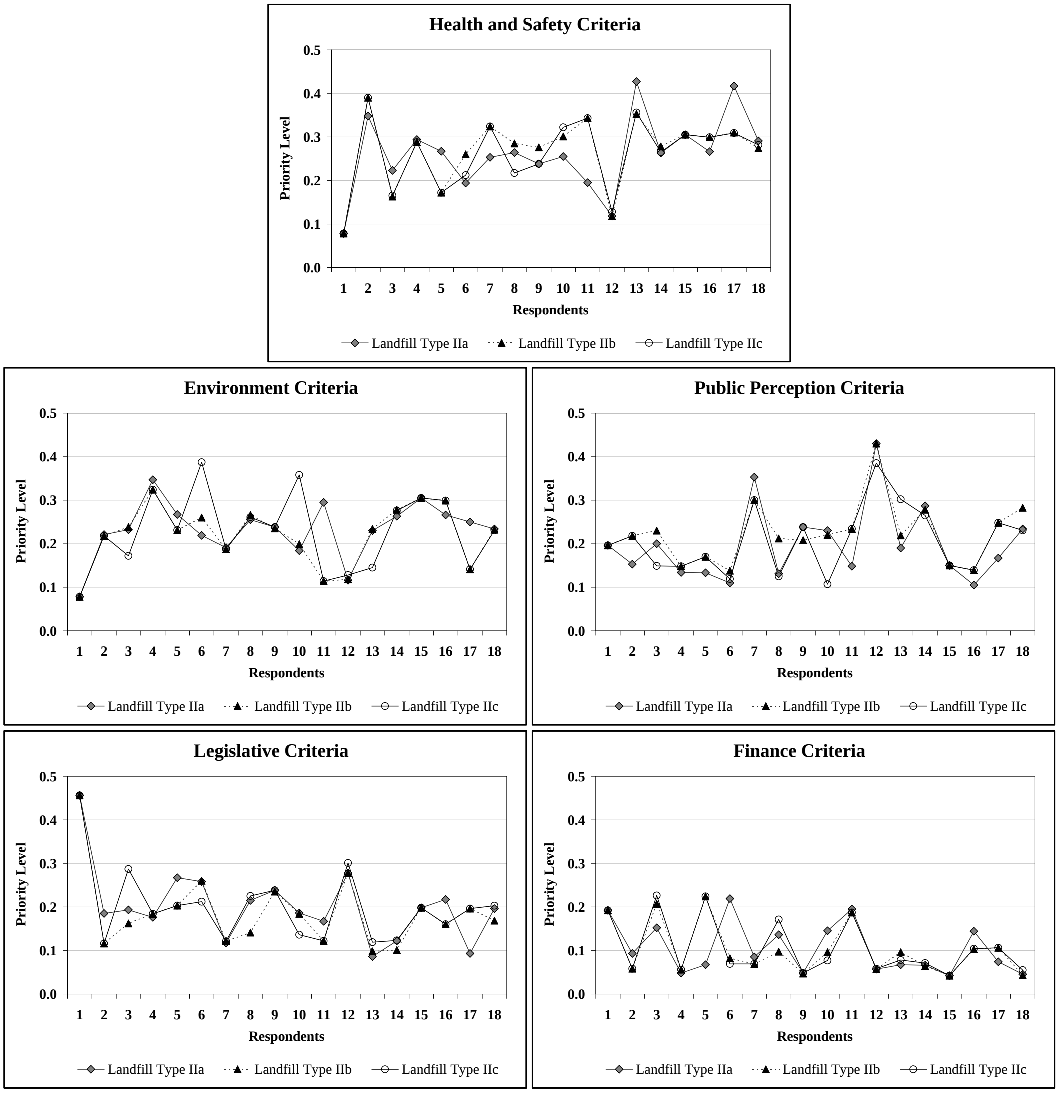

Figure 3b. Survey results (Landfill Type IIa, IIb and IIc)

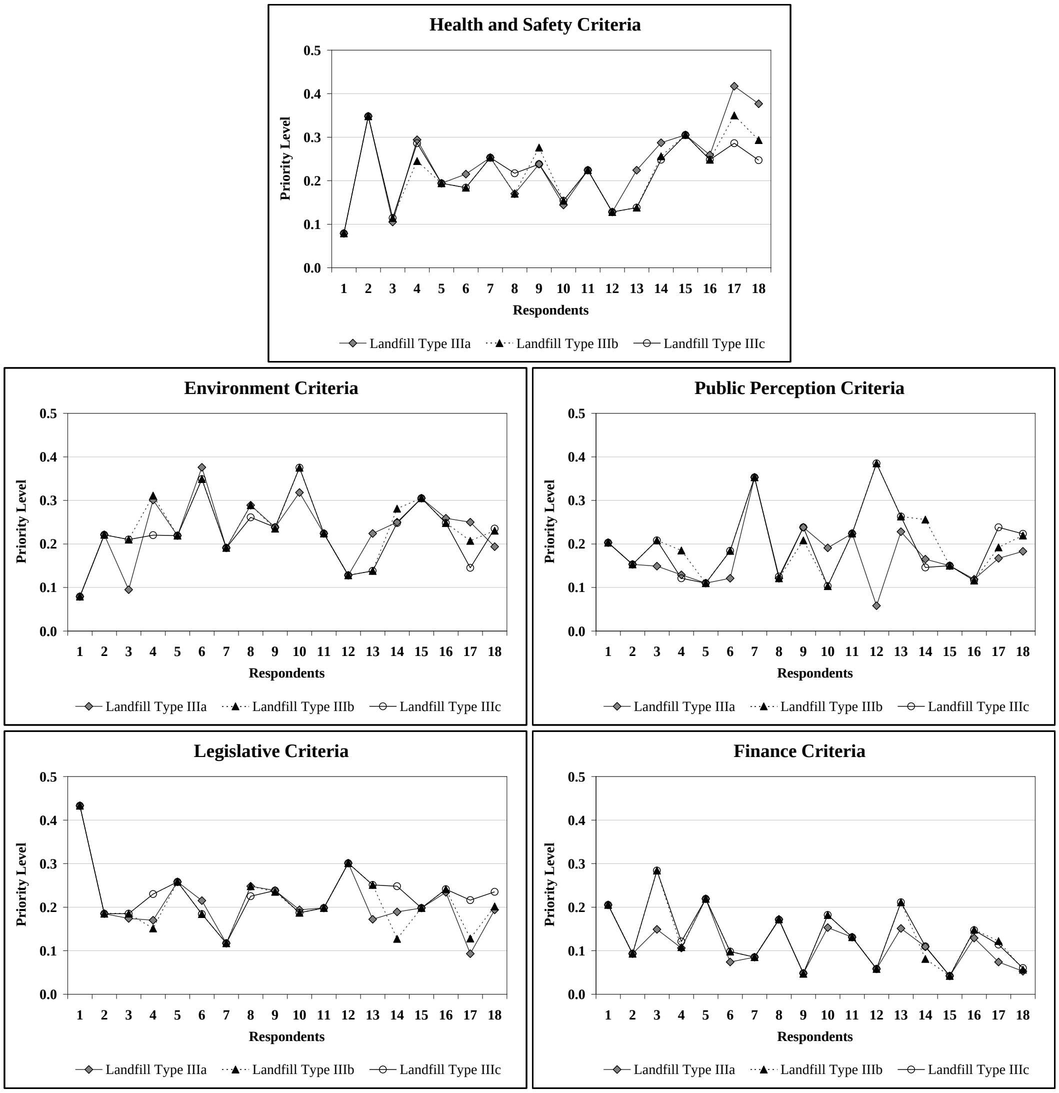

Figure 3c Survey results (Landfill Type IIIa, IIIb and IIIc)

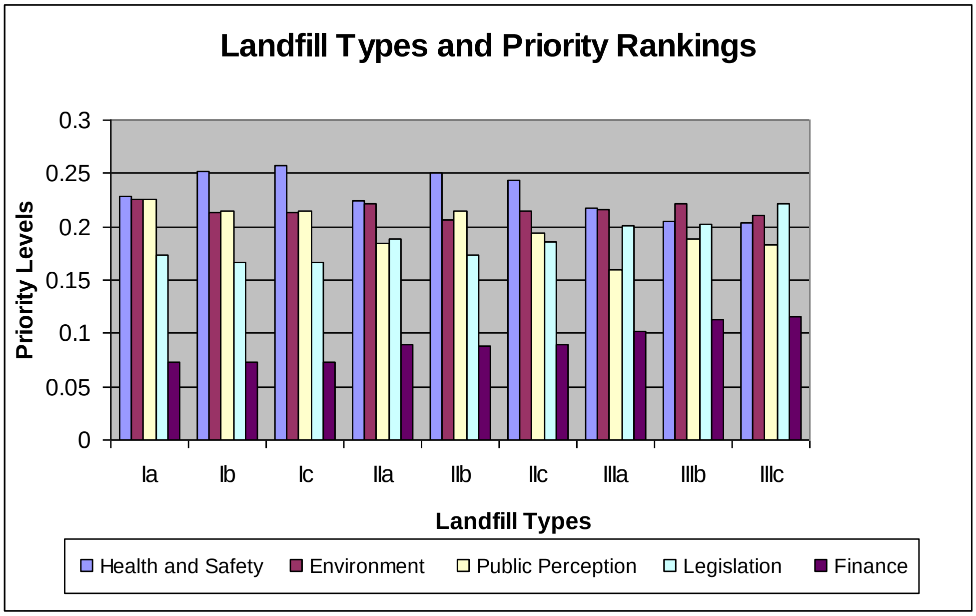

Figure 4. Priority Rankings based on Landfill Type