STUDY OF COMPARISON BETWEEN ANALYTIC HIERARCHY PROCESS (AHP) AND ANALYTIC NETWORK PROCESS (ANP) REGARDING DECISION-MAKING IN GIS

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ABSTRACT

This paper examines the importance of Geographic Information Systems (GIS) over the decision-making process, by a study of comparison between Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP). It provides an overview of the decision-making theory and of Geographic Information Systems (GIS), stressing the importance of understanding both, in order to accomplish the desired results. The paper also includes a case study involving land allocation in Lake Nakuru National Park, Central Kenya. In the first part of the case study, land allocation decisions are made using AHP’s software IDRISI, while in the second part the ultimate goal of Long Term Economic Benefits for the Nakuru area is approached by the creation of a network model via ANP’s software Super-Decisions. A discussion of the Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP), as well as a comparison between them with respect to the results obtained for the case study, enumerating the advantages and disadvantages and also further research ideas, are included.
Dedicated to my loving family in Romania
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CHAPTER 1

INTRODUCTION

Decision-Making and Geographic Information Systems (called from now on GIS), why these two together? What is the link between them?

Research regarding GIS has evolved from the initial focus on technical issues, to concentrating on the need to consolidate the field as a discipline by itself (GIS as science), and more recently to trying to understand the social outreach of the technology. One of the social benefits is “better” decision-making, which has always been considered the promised land of GIS, but not much research has been done to try to understand how (and even if) the introduction of GIS technology impacts the decision-making process (Stevens and Thompson, 1996).

The components of this social process termed decision-making, continue Stevens and Thompson (1996), are data, decision models, the decision environment and people; more data leads to more information, and decision models go a step further by transforming information into knowledge of consequences. By understanding how the rational actor uses a GIS to transform information into knowledge and the changes in the decision environment due to the introduction of the technology one would be able to
improve GIS design, which in turn will lead to better decision-making, the ultimate objective for having the technology in the first place.

GIS can be also defined as a computer-based tool working with spatial data. It is the spatial data that differentiates the GIS from any other information system.

In a GIS the information is derived from the individual data in a spatial database, whereas the knowledge is the understanding of possible consequences based on the information derived from data and a specific line of reasoning (a spatial decision-making model) followed by the GIS user (Figure 1.1) (Stevens and Thompson, 1996).

![GIS Model of Transforming Spatial Data](image)

Figure 1.1: The GIS Model of Transforming Spatial Data

A model represents an object or phenomenon that exists in the real world. A good model is the simplest model that correctly and consistently predicts the behavior of the real world for the phenomena of interest, describing the relationships among data elements in order to predict how events in the real world will occur. The quality of a
model is limited by the data that have been selected and the way that are organized (Epstein, 2002).

Decision-Making can be defined as the process of making a choice between alternatives (Hazelton, 1996).

The components of the decision-making process are: data, decision models, the decision environment and people (Figure 1.2). Each of these components has a direct influence on which alternative gets chosen (Stevens and Thompson, 1996).

Figure 1.2: The Components of Decision-Making (as portrayed by Stevens and Thompson, 1996)
Decision-Making and Geographic Information Systems (GIS) are very much related to one another. The aim of this thesis is to examine their relationship and various facts that link them.

After a discussion of both Decision-Making and GIS in Chapter 2, we will review the basic principles of the two methods of decision-making *Analytic Hierarchy Process* (called from now on **AHP**) and *Analytic Network Process* (called from now on **ANP**) in Chapters 3 and respectively 4. This review will also offer, as a practical application of both decision-making and GIS, a case study involving land allocation in the Lake Nakuru National Park, Kenya.

Using the IDRISI software program for the AHP case, the objective of the first part of the case study (Chapter 5, Part I), is to determine which land areas in Lake Nakuru Area are best suited for industrial use and which ones for residential use, in a complementary land allocation problem. Using the SuperDecisions software program for the ANP case, the objective of the second part of the case study (Chapter 5, Part II), is to create a model for determining the long-term economic benefits of the land allocation. Chapter 6 will follow with a discussion and comparison of the two decision-making methods, as well as of the results obtained. Chapter 7 ends this thesis with conclusions and further remarks. In a larger sense, the objective of this thesis is to study the role that the two methods AHP and ANP can play regarding decision-making in GIS. Using a practical application, like the study of Lake Nakuru National Park, and applying both methods, it becomes clear to us how we can prioritize our decision-making. Moreover, since it is the first time that ANP is being used for decision-making in a GIS, this study could help in further research on the topic.
CHAPTER 2

GIS AND DECISION-MAKING

2.1 AN OVERVIEW OF GEOGRAPHIC INFORMATION SYSTEMS

Geographic Information Systems (GIS) are commonly defined as a marriage or combination of graphic and non-graphic data, in a digital format, as an electronic tool for operations or decision-making. GIS are more globally defined by Moffitt and Bossler (1998), as hardware, software, data, and an environment for operations. Therefore, GIS are flexible decision support tools, which integrate spatial data in a user-friendly format. Spatial data is further defined by Moffitt and Bossler (1998) as features shown on maps or those organized in a digital database that are tied to the surface of the earth by coordinates, addresses, or other means. Lathrop (1999) defines a GIS as a way of organizing information in separate layers and then making a map of composite information. Each layer of information has a theme to it, such as watercourses, vegetation, soils or elevations. The Federal Geographic Data Committee (FGDC) (1997) identified the seven (7) themes common to GIS being: elevation and bathymetry, hydrography, geodetic control, cadastral, transportation, governmental units and orthoimagery. The FGDC’s initiative involves the National Spatial Data Infrastructure
(NSDI) framework of basic geographic data in a common format and an accessible environment that anyone can use and to which anyone can contribute. The seven themes or layers described by the FGDC are not mutually exclusive but are interrelated.

Star and Estes (1990) consider that a Geographic Information System can be of two types: manual (called analog) or automated (called digital). Analog Geographic Information Systems are usually made up of data consisting of maps, transparent materials to be used as overlays, statistical and survey reports, as well as aerial and ground photographs. This data can be compiled and analyzed with instruments like stereo comparators, planimeters, etc. Star and Estes (1990) also write that manual GIS have played an important role in resource management and planning activities, and still have applications, even though is time and space consuming. Manual GIS are usable by everyone, which means that one need not be computer literate to employ manual GIS.

Korte (1997) states that GIS are computer systems that can store virtually any information found on a paper map. A GIS can display maps on a computer screen, and it can provide detailed information about their features, including roads, buildings, and rivers. Moreover the computer can quickly search and analyze these map features and their attributes in ways not possible with paper maps. Unlike analog GIS, digital GIS give the user the ability to browse across an area without interruption, the ability to zoom and change scale freely, though the software and hardware for digital GIS can be hard to understand and typically require training and experience in a variety of geographic, computer-science, and system administration areas. In manual GIS one can observe only in two dimensions, which is not representative for
the real world. Digital GIS allows the decision-maker to view information in a more realistic manner, which means in 3D.

GIS was developed in the mid-sixties as government and university researchers sought to represent the earth's geography using a computer database, display it on a computer terminal and plot it on paper. They also developed computer programs to quickly search and analyze data. Several corporations were founded in the 1970s to develop and sell systems for computer mapping and analysis. The educational and research programs grew through the 70s and the 80s with the GIS approach, and automated mapping systems with the development of databases.

The eighties and nineties came with significant developments in image processing and remote sensing, and also with improvement over the databases. Image-processing systems, developed at the Purdue University Laboratory for Applications of Remote Sensing, incorporated GIS capabilities as the remote sensing community realized that additional GIS data could play an important role in improving the accuracy of the interpretation of remotely sensed data. Between today's two leading GIS software developers, Intergraph Corporation, focused on efficient input and storage of GIS data as well as the preparation of computer-generated maps, and ESRI (Environmental Systems Research Institute) focused on providing a tool kit of computer commands for the analysis of GIS data, which have rounded over the years their systems and capabilities.

There is fierce competition for supremacy in the GIS market.

Korte (1997) states that the typical GIS are founded on several basic concepts. First, real world features on the earth's surface are related to a map grid coordinate system and recorded in the computer. The computer stores the grid coordinates of these features to
show where they are, and the attributes of these map features to show what they are. Second, map features can be displayed or plotted in any combination and at virtually any map scale, making computerized mapping data far more flexible to use than traditional paper maps. Third, a GIS can analyze spatial (locational) relationships among map features (e.g., a GIS can determine how many acres of land zoned for commercial use are located within a town’s flood plain).

2.2 THE SYSTEM

The major components of a GIS are:

➢ user interface;
➢ system/database management capability
➢ database creation/data-entry capacity
➢ spatial data manipulation and analysis packages
➢ display/product generation functions

Peuquet and Marble (1990), showed that there is a trend driven by push and pull factors, regarding handling of geographic data. The push is represented by the limitations of the manual techniques while the pull is toward the use of computers. The reasons for the latter are:

➢ Extremely large and complex data sets can be stored and retrieved more rapidly and with better accuracy when automated.
➢ The techniques and ideas developed by all of the various fields of science would be difficult to understand without the aid of computers and data processing.
2.3 GIS TRENDS

Korte (1997) said that one of the problems that GIS users are facing today is the multitude of formats in which GIS data is stored. This can make difficult to merge data from various sources, or to use a GIS software program and be able to read data created using another program.

The trends regarding Geographic Information System (GIS) are towards the integration, manipulation, presentation and standardization of data of a locational or spatial nature. The research and vision done in this field found the point where the geographic boundaries of distributing GIS are removed, by a new Internet Mapping
system ArcIMS, which provides a powerful framework for distributing and disseminating GIS services on the Internet.

ArcIMS makes it easy to create, design, and manage Internet sites that incorporate e-mapping and e-GIS capabilities. ArcIMS software accesses multiple Internet sites and combines these sites with local data. The ability to access data that is distributed from multiple locations throughout the world is an integral feature to ArcIMS. The sharing of data no longer requires copying or sending data to another site for viewing.

The future of GIS would be the globalization, integration of its applications in almost all of the disciplines and sectors. The Figure 2.2 presents the components of ArcIMS:

Figure 2.2: The Components of an ArcIMS (modified from ESRI’s ArcNews, Fall 1999)
2.4 DECISION-MAKING

The word "decision" derives from Latin word "decidere" meaning "to cut away". It comes from the same root as the Latin word "incidere" meaning "incision"-"to cut in". To decide is to cut away all the other alternatives but one.

A decision is an allocation of resources (Hazelton, 1996), being made by a decision-maker, who's the one who has authority over the resources being allocated. He (she) makes the decision in order to further some objectives, which is what he (she) hopes to achieve by allocating the resources.

The decision-maker will make decisions consistent with his (her) values, which are those things that are important to him (her), especially those that are relevant to this decision. The decision-maker might set a goal for his (her) decision, which is a specific degree of satisfaction of a given objective. Also, the decision-maker might employ decision analysis, which is a structured way of thinking about how the action taken in the current decision would lead to a result. In doing this, one distinguishes three features of the situation: (1) the decision to be made, (2) the chance and unknown events, which can affect the result, and (3) the result itself. Decision analysis then constructs models, logical and perhaps even analytical representations of the relationships within and between these three features on the decision situation. The models then allow the decision-maker to estimate the possible implications of each course of action that he might take, so that he can better understand the relationship between his actions and his objectives.

There are three features in a decision situation: alternatives, uncertainties, and the outcome (Eastman et al., 1993). At the time of the decision, continue Eastman et al., (1993), the decision-maker has available to him at least two alternatives, which are the
courses of action that he might take. When he chooses an alternative and commits to it, he has made the decision and then uncertainties come into play. These are those uncontrollable elements; different alternatives that the decision-maker might choose might subject him to different uncertainties, but in every case the alternatives combine with the uncertainties to produce the outcome. Since the outcome is the result not only of the chosen alternative but also of the uncertainties, it is itself an uncertainty.

Decision-making can occur at a number of levels. It starts at individual level and extends to the deliberation of groups that make up organizations, which in turn make up the overall system of enterprise. This system of enterprise forms part of the total society, which then makes up nations with various compatible and competing ideologies, the total sum of which constitutes the world. Decision-making is an integral part of the management of any organization. Competence in this activity differentiates the manager from the non-manager and, more importantly, the good manager from the mediocre manager. It would be difficult to find any manager who does not consider himself a good decision-maker. Any suggestion given to a manager, which might improve his or her decision-making techniques, almost surely would elicit a highly defensive reaction (Harrison, 1975).

2.5 DEFINITIONS AND EXAMPLES

Decision-making has been defined in a multitude of ways. Hazelton (1996) said that a decision is a choice between alternatives. The alternatives may represent different courses of action, different hypotheses, different land allocations, etc. Rational human behavior involves the evaluation of choice alternatives based on some criteria.
A criterion is some basis for a decision that can be measured and evaluated, so Hazelton continues in saying that a criterion is the evidence upon which a decision is based. Eastman et al., (1993) add that criteria can be of two kinds: factors and constraints.

A factor, is a criterion that enhances or detracts from the suitability of a specific alternative for the activity under consideration; it is therefore measured on a continuous scale. Factors are also known as decision variables in mathematical programming literature and structural variables in the linear programming literature.

A constraint serves to limit the alternatives under consideration. A good example as we’ll see later in the Case Study Part I, is the Park Constraint; Nakuru Lake being a designated National Park, no development can be considered within its boundaries. In many cases constraints will be expressed in the form of a Boolean map – where areas excluded from consideration are coded with a zero and those open for consideration being coded with a one.

According to Eastman et al., (1993), the procedure by which criteria are combined to arrive at a particular evaluation, and by which evaluations are compared and acted upon is known as a decision rule. A decision rule might be simple as a threshold applied to a single criterion or it may be as complex as one involving the comparison of several multi-criteria evaluations. Decision rules typically contain procedures for combining criteria into a single composite index and a statement of how alternatives are to be compared using this index. For example, we might define a composite suitability map for industrial use, based on a weighted linear combination of information on “slope”, “distance from town”, “distance from park”, and “distance from roads”. The rule might further state that the best 4,000 hectares for Industrial and Residential use are to be
selected. This could be achieved by choosing that set of raster cells in which the sum of suitabilities is maximized (1) or it could equally be achieved by rank ordering the cells and taking enough of the highest ranked cells to produce a total of 4,000 hectares (2). The first method is called choice function, while the latter is called choice heuristic. Choice function provides a mathematical mean of comparing alternatives, while choice heuristic specifies a procedure to be followed rather than a function to be evaluated (Eastman et al., 1993).

2.6 DECISION-MAKING, THE SCIENCE

Hazelton (1996) said that decision rules are structured in the context of a specific objective. An objective is thus a perspective that serves to guide the structuring of decision rules. Generally speaking, the research and studies done in the field of decision theory categorize decision analysis being of two kinds — prescriptive and descriptive (Hazelton 1996).

Descriptive decision analysis has the roots in psychology and sociology and focus on explaining why decisions are made in the manner they are (Hazelton, 1996).

Prescriptive decision analysis focuses on the development, evaluation and application of techniques to facilitate decision-making. These studies rely upon the logic of mathematics and statistics, employing the concepts of utility and probability to analyze decision problems. The concept of utility relates to the expression of preferences among alternative options, while probability serves to evaluate the likelihood of these preferences being realized (Hazelton, 1996).
Traditionally, writes Hazelton, (1996), prescriptive decision analysis has taken the form of either an objective or subjective evaluation of decision criteria. In objective analysis, attempts are made to provide a financial appraisal to decision events by identifying all the potential effects and the magnitudes of such impacts based on the market value of events and criteria involved.

Subjective analysis of decision events involves various approaches which share the common purpose of helping decision-makers order their thoughts, express consistent judgments and choose rationally (Cochrane and Zeleny, 1973). The applications of GIS typically fall in subjective type of decision analysis.

According to Eastman et al., (1993), there are three main methodologies used in the implementation of decision theory. These are single criterion with single objective, multiple criteria with single objective, and multiple criteria with multiple objectives.

The actual process of applying the decision rule is called evaluation (Hazelton, 1996). Two of the most common types of evaluation are the multi-criteria evaluation and the multi-objective evaluation.

*Multi-Criteria Evaluation* is the case when several criteria need to be evaluated in order to meet a specific objective. Two of the most common procedures for multi-criteria evaluation are weighted linear combination and concordance-discordance analysis (Voogd, 1983). In the first, each factor is multiplied by a weight and then summed to arrive at a final suitability index. In the latter, each pair of alternatives is analyzed for the degree to which one outranks the other on the specified criteria. Unfortunately, concordance-discordance analysis is computationally impractical when a large number of alternatives are present, such as with raster data, *in which each pixel is an alternative.*
While many decisions we make are prompted by a single objective, it also happens that we need to make decisions that satisfy several objectives. These objectives may be complementary or conflicting in nature (Carver, 1991). With complementary or non-conflicting objectives land areas may satisfy more than one objective. Desirable areas will be those which serve these objectives together in some specified manner, as we’ll see later in the case study with the allocation for industrial and residential uses. Optimal areas would be those that satisfy all of these objectives to the maximum degree possible.

With conflicting objectives, objectives compete for the available land since it can be used for one or the other, but not both. (Rosenthal, 1985) said that is sometimes possible to rank order the objectives and reach a prioritized solution. In these cases, the needs of higher ranked objectives are satisfied before those of lower ranked objectives are dealt with. When this is not possible, and the most common solution to conflict objectives is the development of a compromise solution.

In conclusion, the first thing when we start a multi-objective problem is the question – are these objectives conflicting or not? If they do not conflict, it is a case of complementary objectives, and the problem can often be solved through a hierarchical extension of the multi-criteria evaluation (MCE) process, as in the case study, assigning a weight to each of the objectives and using this with the suitability maps developed for each to combine them into a single suitability map indicating the degree to which areas meet all of the objectives considered. If they conflict, a prioritized solution must be used or compromise must be reached.
2.7 GIS AND DECISION-MAKING

A GIS is an ideal tool to use, analyze and solve multiple criteria problems:

➤ GIS databases combine spatial and non-spatial information.

➤ A GIS generally has ideal data viewing capabilities – it allows for efficient and effective visual examinations of solutions.

➤ A GIS generally allows users to interactively modify solutions to perform sensitivity analysis.

➤ A GIS, by definition, should also contain spatial query and analytical capabilities such as measurement of area, distance measurement, overlay capability, etc.

➤ GIS has also the potential to become a very powerful tool assisting in multiple criteria spatial decision-making and conflict resolution.

➤ Some GIS have already integrated multi-criteria methods with great success, for example IDRISI.

It becomes very clear that information is vital in the process of decision-making.

However, since we rarely have perfect information, this leads to uncertainty, of which two sources can be identified: database and decision rule uncertainty.

2.8 DATABASE UNCERTAINTY

The GIS database is a digital representation of the real world. Any abstraction of reality will contain discrepancies from its source.

Database uncertainty is that which resides in our assessments of the criteria, which are enumerated in the decision rule. Measurement error is the primary source of
such uncertainty. Because of the manner in which slopes are determined there may be some uncertainty about whether a slope that was measured as 35% really is 35%. We may have to admit that there is some finite probability that is as high as 36%. The expression of database uncertainty is likely to rely upon probabilistic theory. However, (Eastman et al., 1993) not all uncertainty relates to measurement error. Uncertainties such as this are best handled with fuzzy set theory. Fuzzy sets are classifications in which the boundaries between classes are not distinct. With fuzzy sets we define a membership function for each class. The function takes values between 0 and 1 in order to measure the grade of membership (possibility) a particular entity has in that class. Typically an S-shaped curve is used to define a membership function between the two end points such that the grade of membership can be defined as possibilities in scale of 0 to 1. The basic procedure can be reviewed with IDRISI for Windows.

2.9 DECISION RULE UNCERTAINTY

Decision rule uncertainty is that which arises from the manner in which criteria are combined and evaluated in order to reach a decision. Nevertheless both sources contribute to the uncertainty of the decision. A very simple form of decision rule uncertainty relates to parameters or thresholds used in the decision rule. A more complex issue is that which relates to the very structure of the decision rule itself. This is sometimes called specification error (Alonso, 1968). When uncertainty is present, the decision rule will need to incorporate modifications to the choice function or heuristic to accommodate the propagation of uncertainty through the rule and replace the hard decision procedures of certain data with the soft ones of uncertainty.
2.10 RISK

Risk may be understood as the likelihood of making a wrong decision, and arises as a result of uncertainty, and its assessment is comprised from both database and decision rule uncertainty (Eastman et al., 1993).

2.11 ASSUMPTIONS

Eastman et al., (1993) established that:

1. The outcome of a decision can itself become a criterion, if it can be predictively modeled, which means that the decision-making process focuses on the development of the decision rule.

2. The ultimate decision is thus a balance between the decision rules applied, the anticipated outcome and the level of risk the decision-maker is willing to assume.

2.12 PARTICIPATORY DECISION-MAKING

Following these assumptions we arrive at a working hypothesis that the decision-making process must be a participatory one if this balance is to be achieved. It is vital that the decision-maker be an active participant in the iterative process of structuring the decision rule, applying it to the available data, assessing its consequences at a given level of risk and subsequently restructuring the decision rule to bring it into closer compliance with an acceptable result. Eventually, the process terminates with the projection of an acceptable result, after which the final implementation is undertaken, as Figure 2.3 best illustrates:
In order to be effective, the decision-maker must participate in this iterative process, but ultimately is the GIS that provide the ability to model and implement the outcome from a specific decision rule. It might happen that if the decision-maker is not strongly involved in the assessment of the projected outcome or somehow not very knowledgeable about GIS, the cycle will be broken. In this context, it happens that the decision rule is implemented by the GIS analyst without a proper assessment, as exemplified in the Figure 2.4:
The term participation has a broader meaning than simply participation in an iterative decision-making process. In many cases there will be more than a single individual with an active interest in the development of the decision. In this case it would be necessary to recognize the very important role of the GIS analyst, as a focus leader working with groups of decision-makers in the iterative process of structuring, evaluating and restructuring a consensus decision rule.

2.13 A FRAMEWORK FOR RESEARCH

While the roles and importance of each actor involved in the decision process might change, the actual decision-makers involved will not. One can expect to find the same people involved in the process before and after the introduction of GIS technology. The observable impact of GIS on the decision-making process will be the introduction of
different decision models that will be used to evaluate the alternatives, and also on the
decision environment (Stevens and Thompson, 1996).

For any attempt made to understand how in fact a GIS can improve decision-making, one
must take in consideration both major factors that influence this (Figure 2.5):

Figure 2.5: Variables that can Influence the Outcome of a Decision in a GIS Environment
(modified from Stevens and Thompson, 1996).

Each one of these variables can influence to a certain extent the choice of which final
alternative of the Decision-Making process gets chosen.
CHAPTER 3

THE ANALYTIC HIERARCHY PROCESS (AHP)

3.1 INTRODUCTION

The Analytic Hierarchy Process (AHP), developed at Wharton School of Business, Pittsburgh, PA, by Thomas Saaty, allows decision-makers to model a complex problem in a hierarchical structure showing the relationships of the goal, objectives (criteria), sub-objectives (sub-criteria), and alternatives (Figure 3.1). Uncertainties and other influencing factors can also be included (Forman & Selly, 2001, p.43).

![Decision Hierarchy Diagram](image)

Figure 3.1: A Decision Hierarchy (Forman & Selly, 2001)
Analytic Hierarchy Process (AHP), writes Saaty (2001, p.23), is a general theory of measurement. It is used to derive ratio scales from both discrete and continuous paired comparisons in multilevel hierarchic structures. These comparisons may be taken from actual measurements or from a fundamental scale that reflects the relative strength of preferences and feelings. The AHP has a special concern with departure from consistency and the measurement of this departure. It has found its widest applications in multicriteria decision-making, in planning and resource allocation, and in conflict resolution.

AHP obtains not only the rank order of the alternatives but also their relative standings measured on a ratio scale facilitating the task of resource allocation, writes Saaty (1990, p. A-51).

AHP is built on a solid yet simple theoretical foundation. The basic model is one that almost every executive is familiar with - a pie chart. If we draw a pie chart, the whole of the chart represents the goal of the decision problem. The pie is organized into wedges, where each wedge represents an objective contributing to the goal. AHP helps determine the relative importance of each wedge of the pie. Each wedge can then be further decomposed into smaller wedges representing sub-objectives, and so on. Finally, wedges corresponding to the lowest level sub-objectives are broken down into alternative wedges, where each alternative wedge represents how much the alternative contributes to that sub-objective. By adding up the priority of the wedges for the alternatives, we determine how much the alternatives contribute to the organization's objectives (Forman & Selly, 2001, p. 50).

AHP is comprised of three major principles:
1. *Decomposition*, or the structuring the problem into a hierarchy (defined by Saaty as a linear structure in which influence is distributed from the top, down) of levels, with a goal, criteria (objectives), sub-criteria (sub-objectives) and alternatives.

2. *Comparative Judgments* applied to construct pairwise comparisons of all combinations of elements in a level with respect to the parent level. These pairwise comparisons are used to derive local priorities of the elements in a level with respect to their parent.

3. *Synthesizing the Priorities (Hierarchic Composition)* is applied to multiply the local priorities of elements in a level by the global priority of the parent element, producing global priorities throughout the hierarchy and then adding the global priorities for the lowest level elements (alternatives), under the form of a priority vector of the alternatives. (Forman & Selly, 2001, p. 51).

In general, hierarchies concern the distribution of a property (the goal) among the elements being compared, to judge which one *influences* or is *influenced* more or has a greater amount of that property (Saaty, 2001, p.4). On the other hand, continues Saaty, *dominance* means greater influence with respect to a certain property. To say that one element dominates another is a generic way of saying that it is greater or more important, more preferred, or more likely to occur than another element and the question that one asks would be: *"with respect to an attribute, which of two elements has the attribute or meets that criterion more than another element, and how much more?"*

There are two kinds of dominance among elements: the first has to do with the possession of a property, which we call *direct dominance*, and the second has to do with influencing other elements with respect to a property which we call *indirect dominance*. 
For *direct dominance* we compare elements in pairs to determine which one has more of a property, while for the *indirect dominance* we compare elements in pairs to determine the dominance of their influence on a third element with respect to a property.

### 3.2 PAIRWISE COMPARISON AND THE AHP’s SCALE

Pairwise comparisons (Forman & Selly, 2001 p. 62) of the elements at each level of an model are made in terms of either:

*Importance* - when comparing objectives with respect to their relative importance.

*Preference* - when comparing the preference for alternatives with respect to an objective.

*Likelihood* - when comparing uncertain events or scenarios with respect to the probability of their occurrence.

Pairwise comparisons, Forman & Selly continue, are basic to the AHP methodology. When comparing a pair of “factors”, a ratio of relative importance, preference or likelihood of the factors can be established. This ratio need not be based on some standard scale such as feet or meters but merely represents the relationship of the two “factors” being compared. For example, when looking at two lights, we can judge (without any scientific measurement) that one light is brighter, or perhaps twice as bright as the other. This may be a subjective judgment, but the two lights can be compared as such. Most individuals would question the accuracy of any judgment made without using a standard scale. Yet, it has been verified that a number of these pairwise comparisons taken together form a sort of average, the results of which are very accurate. This “average” is calculated through a complex mathematical process using eigenvalues and eigenvectors. The results of this method have been tested experimentally and have been found to be extremely accurate.
(Saaty, 1980). This method is used in AHP allowing one to use both subjective and objective data in making pairwise comparisons.

According to Saaty’s categorization we have four fundamental scales (levels of measurement) ranging from lowest to highest, each level having all the meanings of the levels below plus additional as follows:

- **Nominal Scale**: used for identification purposes only and imply nothing about ordering.

- **Ordinal Scale**: implies an order or ranking among elements. It does not imply anything about the differences between items.

- **Interval Scale**: possesses the meaning of the Nominal and Ordinal scales, and has meaning in regard with interval between objects. Because corresponding intervals on different parts of an interval scale have the same meaning, it can be used in arithmetic operation of addition and multiplication.

- **Ratio Scale**: is the highest level, having Nominal, Ordinal, and Interval properties as well as the properties of ratios. Corresponding ratios on different parts of a ratio scale have the same meaning. Different ratio scales can be multiplied and divided and still give rise to a ratio scale, moreover it is easier to think of a ratio scale as one for which equivalent ratios are considered equal (Adapted from Forman & Sally, 2001, p. 33-34).

Paired comparisons judgments in the AHP are applied to pairs of homogeneous elements. When the elements are not homogeneous, they are separated into clusters of
homogeneous elements with a common element shared by two consecutive clusters. The fundamental scale of values for representing the strength of judgments is shown in the Figure 3.2:

<table>
<thead>
<tr>
<th>Numerical Value</th>
<th>Verbal Scale</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Equal importance of both elements</td>
<td>Two elements contribute equally</td>
</tr>
<tr>
<td>3.0</td>
<td>Moderate importance of one element over another</td>
<td>Experience and judgment favor one element over another</td>
</tr>
<tr>
<td>5.0</td>
<td>Strong importance of one element over another</td>
<td>An element is strongly favored</td>
</tr>
<tr>
<td>7.0</td>
<td>Very strong importance of one element over another</td>
<td>An element is very strongly dominant</td>
</tr>
<tr>
<td>9.0</td>
<td>Extreme importance of one element over another</td>
<td>An element is favored by at least an order of magnitude</td>
</tr>
<tr>
<td>2.0, 4.0, 6.0, 8.0</td>
<td>Intermediate values</td>
<td>Used to compromise between two judgments</td>
</tr>
</tbody>
</table>

Figure 3.2: The AHP’s Fundamental Scale (Forman & Selly 2001, p. 68)

This scale, continues Forman & Selly, was derived from the basic mathematics of neural firing that leads to the well-known law of *stimulus-response*, which says that quantitatively, people have the capacity to divide their response to stimuli into three categories: *high, medium and low*. They also have the capacity to refine this division by further subdividing each of these intensities of responses into high, medium and low, thus yielding in all nine subdivisions. Also, regarding the stability of the eigenvectors of the
priorities, there are conditions, requiring that the elements being compared to be homogeneous, which limits the upper value of the fundamental scale to 9.

3.3 EIGENVECTORS, EIGENVALUES AND CONSISTENCY

AHP allows for the application of data, experience, insight, and intuition in a logical and thorough way. AHP enables decision-makers to derive ratio scale priorities or weights as opposed to arbitrarily assigning them. In so doing, AHP not only supports decision-makers by enabling them to structure complexity and exercise judgment, but also allows them to incorporate both objective and subjective considerations in the decision process. AHP is a compensatory decision methodology because alternatives that are deficient with respect to one or more objectives can compensate by their performance with respect to other objectives.

AHP is composed of several previously existing but unassociated concepts and techniques such as hierarchical structuring of complexity, pairwise comparisons, redundant judgments, an eigenvector method for deriving weights, and consistency considerations. By using the AHP pairwise comparison process, weights or priorities are derived from a set of judgments. While it is difficult to justify weights that are arbitrarily assigned, it is relatively easy to justify judgments and the basis (hard data, knowledge, experience) for the judgments. These weights or priorities are ratio level measures. There are an infinite number of ways to derive the vector of priorities from the reciprocal matrix of comparisons $\mathbf{A} = (a_{ij})$. Only one of them is the correct one, a fact that has been proved
mathematically. Allowing for a degree of inconsistency, and the need to capture dominance lead to an eigenvalue formulation. (Saaty 2001, p.55).

Suppose we already knew the relative weights of a set of physical objects like n rocks. We can express them in a pairwise comparison matrix as follows (Figure 3.3):

\[
A = \begin{bmatrix}
\frac{w_1}{w_1} & \frac{w_1}{w_2} & \frac{w_1}{w_3} & \cdots & \frac{w_1}{w_n} \\
\frac{w_2}{w_1} & \frac{w_2}{w_2} & \frac{w_2}{w_3} & \cdots & \frac{w_2}{w_n} \\
\frac{w_3}{w_1} & \frac{w_3}{w_2} & \frac{w_3}{w_3} & \cdots & \frac{w_3}{w_n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{w_n}{w_1} & \frac{w_n}{w_2} & \frac{w_n}{w_3} & \cdots & \frac{w_n}{w_n}
\end{bmatrix}
\]

Figure 3.3: The Pairwise Comparison Matrix (Forman & Selly 2001, p. 63)

If we wanted to "recover" or find the vector of weights, \([w_1, w_2, w_3, \ldots w_n]\) given these ratios, we can take the matrix product of the matrix A with the vector w to obtain (Figure 3.4):
Figure 3.4: The Matrix Product of the matrix $A$ with the vector $W$ (Forman & Selly 2001, p. 64)

Where $w_i$, $i = 1,..n$ represent the derived ratio scale values (weights). If we knew $A$, but not $w$, we could solve the above for $w$ (Forman & Selly 2001, p. 63 - 64).

The problem of solving for a nonzero solution to this set of equations is very common in engineering and physics and is known as an eigenvalue problem:

$$A \cdot w = \lambda \cdot w \; \text{(1)}$$

The solution to this set of equations is, in general, found by solving an nth order equation for (1). Thus, in general, there can be up to $n$ unique values for (1), with an associated $w$ vector for each of the $n$ values. In this case however, the matrix $A$ has a special form since each row is a constant multiple of the first row. For such a matrix, the rank of the matrix is one, and all the eigenvalues of $A$ are zero, except one. Since the sum of the eigenvalues of a positive matrix is equal to the trace of the matrix (the sum of the diagonal elements), the non-zero eigenvalue has a value of $n$, the size of the matrix. This
eigenvalue is referred to as $\lambda_{\text{max}}$. Notice that each column of A is a constant multiple of w. Thus, w can be found by normalizing any column of A. If $a_{ij}$ represents the importance of alternative i over alternative j and $a_{jk}$ represents the importance of alternative j over alternative k, then, to conform to the transitivity, the importance of alternative i over alternative k, must equal $a_{ij} \cdot a_{jk}$ (2), for the judgment to be consistent. The matrix A is said to be strongly consistent if:

$$a_{ik} \cdot a_{kj} = a_{ij} \quad (3),$$
for all $i,j$

Considering the case where we do not know w, and where we have only estimates of the $a_{ij}$'s in the matrix A, the strong consistency property most likely does not hold. (This allows for small errors and inconsistencies in judgments). It has been shown that for any matrix, small perturbations in the entries imply similar perturbations in the eigenvalues, thus the eigenvalue problem for the inconsistent case is:

$$A \cdot w = \lambda_{\text{max}} \cdot w$$

where $\lambda_{\text{max}}$ will be close to n (actually greater than or equal to n) and the other $\lambda$'s will be close to zero. The estimates of the weights for the activities can be found by normalizing the eigenvector corresponding to the largest eigenvalue in the above matrix equation.

The closer is to n, the more consistent the judgments. Thus, the difference, $\lambda_{\text{max}} - n$, can be used as a measure of consistency (this difference will be zero for perfect consistency). Instead of using this difference directly, Saaty (1980, p. 51) defined a consistency index as:

$$\text{C.I.} = (\lambda_{\text{max}} - n)/(n-1)$$

since it represents the average of the remaining eigenvalues.
Saaty (1980, p.51) defines the *consistency ratio* (C.R.) as the ratio of the *consistency index* (C.I.) or the “closeness to consistency” to the average *random index* (R.I.) for the same order matrix. A consistency ratio of 0.10 or less is considered acceptable.

\[
\text{C.I.} = \frac{\lambda_{\text{max}} - n}{n - 1} \quad \text{where} \quad \lambda_{\text{max}} = \text{the principal eigenvalue}
\]

\[n = \text{the number of activities in the matrix}\]

The closer \(\lambda_{\text{max}}\) is to \(n\), the more consistent is the result.

R.I. also called the *random index* is the consistency index of a randomly generated reciprocal matrix from the scale 1 to 9, with the reciprocals forced. This was statistically determined by researchers at Oak Ridge National Laboratory, who generated an average R.I. for matrices of order 1-15 using a sample size of 100. One would expect the R.I. to increase as the order of the matrix increases. The following table (Figure 3.5) gives the order of the matrix (first row) and the average R.I. (second row) determined as described above.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
<td>1.51</td>
<td>1.48</td>
<td>1.56</td>
<td>1.57</td>
<td>1.59</td>
</tr>
</tbody>
</table>

*Figure 3.5: Table of Consistency Ratios for Different Matrix Orders*

Because of the reciprocal property of the comparison matrix, the eigenvector problem can be solved by raising the matrix to the \(n\)th power, and taking the limit as \(n\) approaches infinity (as we’ll see later in the ANP case). The matrix will always converge.
An easy way to get an approximation to the priorities is to normalize the geometric mean (the nth root of the product of the elements) in each row, the result will coincide with the eigenvector for n =< 3.

3.4 RANK REVERSAL PROBLEM

Rank reversal as defined by Saaty (2001, p.41) is the process of a change in rank among already-ranked alternatives on a set of criteria, when a new alternative is added to the group or an old one is deleted, and no additional criteria are introduced or deleted. There are pro and contra opinions whether rank should be preserved. One part said that the rank should always be preserved, since the other claims that rank reversals do occur in practice and any theory or model should reflect that fact.

There are many examples in which rank reversal does occur for reasons like discovery of an abundance of an existing alternative, or the addition of a high quality alternative, which defines the quantitative and qualitative property of the rank reversal.

Since rank reversal has been documented in the literature and it has been experimentally shown that it does occur, it is not difficult to construct decisions in which rank should be preserved, but on changing the names of the criteria and the alternatives but not of any of the judgments, rank needs to be allowed to reverse (Saaty, 2001). It is the call of the decision maker to determine whether to preserve the rank or not.

Summary of the AHP

The AHP provides the objective mathematics to process the inescapably subjective and personal preferences used in making a decision. With the ANP, one
constructs hierarchies, then makes judgments or performs measurements on pairs of elements with respect to a controlling element to derive ratio scales, which are then synthesized throughout the structure to select the best alternative.

Fundamentally, the AHP works by developing priorities for the alternatives and the criteria used to judge the alternatives.

First, priorities are derived for the criteria in terms of their importance to achieve the goal. Second, the priorities are derived for the performance of the alternatives on each criterion. These priorities are derived based on pairwise comparisons using judgments, or ratios of measurements from the AHP's scale. Finally a weighing and adding process is used to obtain overall priorities for the alternatives as to how they contribute to the goal.

Saaty (1999) says that structure of AHP is sustained by seven pillars, which are:

1) ratio scales, derived from reciprocal paired comparisons.

2) paired comparisons and the psychophysical origin of the AHP's fundamental scale used to make the comparisons.

3) conditions for sensitivity of the principal eigenvector to changes in judgments.

4) homogeneity and clustering.

5) additive synthesis of priorities.

6) allowing rank preservation (ideal mode) or allowing rank reversal (distributive mode).

7) group decision-making using a mathematical way for synthesizing individual judgments which allows the construction of a group decision compatible with the individual preferences. (Summary adapted from Saaty, 1999, pp. 1-15).
AHP will be extensively used in the first part of the case study. Employing the following principal modules: Weight, Multi-Criteria Evaluation (MCE) and Rank, in the IDRISI software, which relies on the AHP methodology, will be used in helping us reach a Multi-Objective/Multi-Criteria decision with complementary objectives regarding land allocation.
CHAPTER 4

THE ANALYTIC NETWORK PROCESS (ANP) WITH DEPENDENCE AND FEEDBACK

4.1 INTRODUCTION

Many decision problems cannot be structured hierarchically because they involve the interaction and dependence of higher-level elements on lower-level elements. Not only does the importance of the criteria determine the importance of the alternatives as in a hierarchy, but also the importance of the alternatives themselves determines the importance of the criteria. Feedback enables us to factor the future into the present to determine what we have to do to attain a desired future (Saaty, 2001, p.83).

The feedback structure does not have the linear top-to-bottom form of a hierarchy but looks more like a network, with cycles connecting its components of elements, which we can no longer call levels, and with loops that connect a component to itself. It also has sources and sinks.

Saaty (2001) states that for deriving priorities in a system with interdependent influences, the feedback approach, a generalization of the idea of a hierarchy, is used. Hence, the ANP is a generalization of AHP.
ANP models problems of systems in which the relationship between components (the counterparts of levels in a hierarchy) cannot be represented as higher or lower. These systems are known as "systems with feedback", where systems of components (clusters) may be regarded as elements (nodes) that interact and influence each other with respect to a criterion or property.

Unlike the hierarchy, which has a linear top-to-bottom form, the feedback structure looks more like a network, with cycles connecting its components of elements, and with loops that connect a component to itself, as exemplified below in the Figure 4.1:

Figure 4.1: Feedback Network with Components having Inner and Outer Dependence (modified from Saaty, 2001)
4.2 DEFINITIONS

A source component is an origin of paths of influence and never a destination of such path (i.e. C₄ in figure 4.1). A sink component is a destination of paths of influence and never an origin of such paths (i.e. C₁ in figure 4.1). Those components whose arrows both enter and exit are known as transient components (i.e. C₂ and C₃ in figure 4.1).

In a network, the components are not arranged in a particular order, but are connected appropriately in pairs with directed lines. An arrow points from one component to another to simulate the influence of the elements of the second component on those in the first component, influence that is otherwise called dominance, which refers to the amount of influence with respect to a certain property. The pairwise comparisons of elements in a component are made according to the dominance or influence of each other member of a pair on an element in the same or in another component.

Additionally, in a network, the system of components may be regarded as elements that interact and influence each other with respect to a criterion or property. That property itself must be of a higher order of complexity than the elements contained in the components and it is called a control criterion. The result in such control criterion serves as the basis for all comparisons made both for the components and for their elements.

Influence is too general a concept and must be specified in terms of particular criteria being analyzed according to each criterion and then synthesized by weighting with these priorities of the "control" belonging to a hierarchy or to a system (Saaty, 2001).
Two major questions form the basis of ANP (Saaty, 2001, p.93):

1. Given a criterion, which element has greater influence (is more dominant) with respect to that criterion?

2. Given a criterion and given an element X in any component, which element in the same or in a different component has greater influence on (or is influenced by) X with respect with that criterion?

4.3 THE FEEDBACK NETWORK; WEIGHTING THE COMPONENTS

In general a network consists of components and elements in this components. Sometimes, in the process of creating structures to represent problems, there may be larger parts to consider than components. Ranked according to size, we have a system that is composed by subsystems, with each subsystem made up by components, and each component being made up by elements.

Also in a network, the elements in a component may influence other elements in the same component (inner dependence) and those in other components (outer dependence) with respect to control criterion. What we really want to determine is the overall influence of all the elements in the network and in particular the alternatives of the decision. In doing so we must organize the properties or criteria and prioritize them in the framework of a network, perform comparisons and synthesize to obtain the priorities of these properties. We then derive the influence of elements in the feedback system with respect to each of
these properties, and finally weighting the resulting influences by the importance of the properties and add to obtain the overall influence of each element.

By using ANP one needs to prioritize the influence of the components on each other component to which the elements belong. This is assessed through paired comparisons with respect to a control criterion. It’s not only the priority of the components that matter but this is used in weighting the priorities of all the elements in that component. The reason for doing this, says Saaty (2001), is to enable us to perform feedback multiplication of priorities by other priorities in a cycle, an infinite number of times, until they converge. However the process would not converge unless the resulting matrix of priorities is column stochastic (columns of the matrix sum to unity and all the elements are non-negative). The stochastic matrix is created to reveal the measure of relative influence of all elements in the system with respect to each element in that system.

4.4 THE SUPERMATRIX

Thomas L. Saaty introduced the “supermatrix” approach in late eighties, in order to handle the interdependence among elements by obtaining the composite weights.

We denote a component of a decision network by $C_h, h = 1,2,...,N$ and assuming that it has $n_h$ elements, which we denote by $e_{h1}, e_{h2},...,e_{h,n_h}$. The influences of a given set of elements in a component on any element in the system is represented by a priority vector derived from paired comparisons, in the usual way of the AHP. It is these derived vectors, how they are grouped and arranged, and how to use the resulting structure which turns out to be the supermatrix, that is of a interest to us (Saaty, 2001, p.86). The
supermatrix is used to represent the flow of influence from a component to itself ($C_3$ Figure 4.1), and to the other components, thus the influence of elements in the network on other elements in that network as below (Figure 4.2), being called The Supermatrix:

![Supermatrix Diagram]

**Figure 4.2:** The Supermatrix with Components and Elements (modified after Saaty, 2001).

A typical entry $W_{ij}$ in the supermatrix is called a *block of the supermatrix*, and it is a matrix of the form (figure 4.3):
Each column $W_{ij}$ is a principal eigenvector of the influence of the elements in the $i$-th component of the network on an element in the $j$-th component. Some of the entries may be zero corresponding to those elements that have no influence, thus we don’t need to use all elements in a component when we make the paired comparisons to derive the eigenvector, but only those that have a non-zero influence (Saaty, 2001, p.88).

As a particular case, a network may be generated from a hierarchy by increasing the hierarchy’s connections gradually so that pairs of components are connected as desired and some components have an inner dependence loop (figure 4.4):
Figure 4.4: A Particular Case of a Network (modified after Saaty, 2001).

An entry in a supermatrix of a hierarchy is a block $W_{ij}$ positioned where the $i$-th component is connected to and influences the $j$-th level immediately above.

In this particular case of transforming a hierarchy in a feedback network, the last entry in the last row and column of a supermatrix of a hierarchy is the identity matrix $I$. It corresponds to a loop at the bottom level, used to show that each element depends only on itself. The supermatrix for a hierarchy will look like in the figure (4.5):
Figure 4.5: The Supermatrix for a Hierarchy (modified after Saaty, 2001).

4.5 CONTROL CRITERIA

For the reasons of clarity and greater precision, the influence represented in all derived eigenvectors of priorities entered in a supermatrix must be measured according to single criterion, such as economic influence (as we’ll see later in chapter 5 part II). We call such criteria (property) with respect to which influence is represented in individual supermatrices, control criteria. Our declared purpose being to determine the measure of the priority of overall influence of all the elements in the network and in particular the alternatives of the decision, for which we have to combine all the influences obtained from the limit of the supermatrix, it becomes imperative to group the control criteria in a structure that allows to derive priorities for them and use these priorities to weight the
corresponding individual supermatrix limits. As we have already stated, we call this structure *control criterion*.

There are two types of control criteria. One is directly connected to the structure as the goal of a hierarchy (if the structure is in fact a hierarchy), in which case the control criterion is called a "comparison – linking" criterion. The other one, where a control criterion does not connect directly to the structure but induces comparisons in the network is called a "comparison – inducing" criterion (Saaty, 2001, p. 91-92).

4.6 THE WEIGHTED SUPERMATRIX

With the supermatrix already composed, we are now ready to derive the limit priorities of influence from it. In order to do so, the supermatrix must be first transformed to a matrix each of whose columns sums to unity, called a *stochastic* matrix.

"Is there a natural way to transform a given supermatrix whose columns usually sum to more than one, to a stochastic matrix?" (Saaty, 2001, p.94)

The explanation, continues Saaty, comes from the fact that the priority of an element in a component is an inadequate indicator of its priority in the entire set of components. The highest priority element in a component need not be the highest priority element in the set of components. This is obvious because each component has a highest ranked element and they cannot all be first in the network. Thus we need to compare the components themselves according to their influence on each component in the supermatrix with respect to the *control criterion*. The comparisons give rise to a derived vector of priorities of influence of all the components (on the left of the supermatrix) on each component on top. The resulting vectors are each used to weight the blocks of matrices that fall in the
column under the given component. The first entry of the vector (11) is multiplied by all the elements in the first block of that column \((W_{11})\), the second (12) by all the elements in the second block \((W_{12})\) of the column and so on. In this way we weight the blocks in each column of the supermatrix. The result is known as the\textit{ weighted supermatrix}, which is now stochastic. It is this stochastic matrix that we can work to derive the desired priorities by transforming it to a \textit{limit supermatrix}, which yields the long run or limit priority of influence of each element on every other element.

4.7 \textsc{The Limit Supermatrix and the Cesaro Sum}

As stated previously, the entries of the weighted supermatrix itself give the direct influence of any element on any other element, so what we need to do is to capture the transmission of influence along all possible paths of the supermatrix.

Not all the influences are defined in a direct way (pointed by arrows) since an element can influence a second element indirectly through its influence on some third element and then by influence of that element on the second. All the indirect influences are obtained by squaring the weighted supermatrix. One must also consider the case when the influence of one element on another can occur by considering a third element that influences fourth element, which in turn influences the second element. All such influences are obtained from the cubic power of the matrix and so on. Thus we have a infinite sequence of influence matrices denoted by \(W^k \) where \(k = 1,2,\ldots\) as exemplified in the Figure 4.6:

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We are interested to know if the result is convergent and its limit is unique and not least how do we compute this limit to obtain the desired priorities.

If we take the limit of the average of a sequence of \( N \) of these powers of the supermatrix, known as Cesaro Sum, we get \( \lim_{k \to \infty} (1/N) \sum_{k=1}^{N} W^k \), known as the Limit Supermatrix (Saaty, 2001, p.96).

It is known from the mathematical analysis that if a sequence converges to a limit, then its Cesaro sum converges to the same limit. Also it is known from the Jordan Canonical Form of a stochastic matrix \( W \), whose \( \lim_{k \to \infty} W^k \) exists (since our sequence is
defined by the powers of the supermatrix), that it is sufficient to find out what the limit of these powers is.

Even though we are not sure whether the sequence converges to a unique limit, the Cesaro Sum averages out over the different limits of the sequence, obtaining a unique limit.

There are four major cases to consider in deriving the limit supermatrix depending on the simplicity or multiplicity of the principle eigenvalue and on the reducibility and irreducibility of the supermatrix.

With respect to the principle eigenvalue, there are essentially three cases to consider:

1. \( \lambda_{\text{max}} = 1 \) is a simple root and there are no other roots of unity.

2. there are other roots of unity that cause cycling, whether \( \lambda_{\text{max}} = 1 \) is simple or multiple.

3. \( \lambda_{\text{max}} = 1 \) is a multiple root.

With respect to reducibility-irreducibility, Saaty (2001, p.107) says that the concept of an irreducible-reducible matrix is due to Forbenius, in which a nonnegative matrix \((a_{ij})\) is irreducible if the graph (with as many nodes as the order of the supermatrix) corresponding to the matrix is strongly connected (there's always a path from a node to any other node). Thus an irreducible matrix cannot have source or sink nodes. Algebraically, a nonnegative matrix is irreducible if it cannot be reduced or decomposed into the form:

\[
\begin{pmatrix}
W_1 & 0 \\
W_2 & W_3
\end{pmatrix}
\]
Where $W_1$ and $W_3$ are square submatrices. Otherwise, it is said to be reducible. Further, an irreducible matrix has a largest eigenvalue that is simple. If $W$ is stochastic then we know that $\lambda_{\text{max}} = 1$. An irreducible matrix is either primitive, or cyclic (cases 1 or 2 above).

Narrowing the possibilities to two cases for computation, we begin by raising the stochastic matrix $W$ to the powers and read off the priorities. If the powers do not converge to a single matrix whose successive values improve in accuracy, we know that the outcome belong to a cycle whose length is determined by taking successive large powers of $W$. In that case, we take the average (Cesaro Sum) of the successive matrices of an entire cycle for the final priorities.

4.8 SUPER-DECISIONS FOR AHP

The ANP software Super-Decisions, used in the part two of the case study, was developed by William Adams and Rozann W. Saaty. It does the calculations automatically without having to go through different cases. It is composed of a main network and subnetworks, each subnetwork being attached to a control node in the network above, and it is possible to have many layers of subnetworks. Generally, the alternatives of the ANP model are in the lowest level subnetwork. The priorities of the alternatives are synthesized up through the layers of subnetworks to the top network.

Super-Decisions first tests for irreducibility, and unless there is cyclicity for which the Cesaro Sum would be calculated, it (the program) obtains the outcome for the primitivity as the limit powers of $W$. If irreducibility fails, it again raises $W$ to the large powers. The result is that in all cases the matrix is raised to powers, with the Cesaro sum
used when there is cyclicity, recognized by noting the successive powers of the matrix yield different limit outcomes (Saaty, 2001, p.112).

The overall priorities of the elements and alternatives with respect to the corresponding control criterion can be read off the supermatrix as given or they may be structurally adjusted according to the number of elements in each cluster and appropriately re-weighted.

**Summary of the ANP**

The ANP is a new theory that extends AHP to cases of dependence and feedback. It allows interaction and feedback within clusters (inner dependence) and between clusters (outer dependence). Feedback can better capture the complex effects of interplay in human society. The ANP provides a thorough framework which includes clusters of elements connected in any desired way to investigate the process of deriving ratio scale priorities from the distribution of influence among elements and among clusters.

Network models do not have levels such as goal, objectives and alternatives, like the ANP. Instead, the elements (or nodes) in a network model are grouped into clusters, such as objective clusters and alternative clusters. The flow of influence in a feedback network is specified by links. A link from objectives to alternatives specifies the influence can flow from the former to the latter, and conversely, when pairs of elements can be meaningfully compared with respect to another element, then a link from the latter to the former is appropriate. One way to identify all possible links is to consider each element and identify all other pairs of elements that can be logically compared with respect to the element being considered.
When making pairwise comparisons in an ANP model, the questions are formulated in terms of dominance and influence. When comparing a pair of elements in one cluster with respect to an element in another (or the same) cluster, we ask either:

Which element of the pair has greater influence?, or

Which element of the pair is influenced more?

In the ANP we are usually looking for a prioritization of alternatives as a result, hence every feedback model should include a cluster of elements that will be our alternatives.

Concluding, the following are steps in building a Feedback Network:

- identify the clusters (components) as they relate to the problem
- identify the elements (nodes) within each cluster
- identify dependencies among the elements and link them
- elicit judgments on the elements
- elicit judgments on the clusters
- synthesize the results

(Summary adapted from Forman & Selly, 2001, pp. 328-330 and Saaty, 1997).
CHAPTER 5

A CASE STUDY: LAKE NAKURU NATIONAL PARK

PART I: THE ANALYTIC HIERARCHY PROCESS APPROACH

5.1 BACKGROUND

Lake Nakuru National Park is located in the Great Rift Valley of Central Kenya, approximately 150 kilometers northwest of Nairobi, the capital of Kenya. A small portion of the lake was originally established as a bird sanctuary in 1961. In 1968 the entire lake and shoreline were declared as a National Park. Both wild animals and large herds of cattle grazed the grasslands bordering the shore. In 1974 the park's borders were expanded to include the large plain south of the lake and extended areas around the rest of the perimeter. The 1974 border remains today, enclosing a total area of 188 square kilometers (Eastman et al., 1993).

The park was enclosed with 74 kilometers of electric fencing in 1987 to provide security for the wildlife and to keep the animals from leaving the park and damaging nearby farm fields. The park is known for its wide variety of bird species, including immense flocks of pink flamingoes, and other wildlife including rhinos and waterbucks. In 1990, the Kenyan government designated Lake Nakuru a site of international importance.
The area surrounding the park has undergone significant demographic changes in the last years. Contiguous resettlement areas have replaced the once thinly populated cattle ranches on the western part of the park. Nakuru town, located just outside the northwest park gate is Kenya’s third largest urban area and is rapidly growing.

Substantial industry, mostly light industry associated with the processing of agricultural products, has developed and continues to support further expansion. Still, tourism and related activities are very important to the economy of Nakuru town and the surrounding area, and the park and its wildlife are the major tourist attractions. Though the electric fence effectively keeps an encroaching population out of the park, it is unable to prevent the entrance of the environmental problems associated with the population.

The challenge facing planners in the area is to effectively balance development and economic growth with environmentally sound practices so as to guard against environmental degradation both outside and inside the park. This is a difficult agenda given the rapid population growth of the urban area, tourist flow, and the subsequent increased demand on the surroundings for housing and industrial facilities.

Basic data on Lake Nakuru National Park that was used in this researcher’s case study will provide the basis for two hypothetical cases. The first will be presented as two Single-Objective/Multi-Criteria evaluations, whereas the second will extend the logic to a Multi-Objective/Multi-Criteria evaluation.

To gain an overview of Nakuru township and its surroundings, a three-dimensional orthographic perspective image of the study area was produced by the United Nations (UNEP/GRID) using LANDSAT imagery (Figure 5.1) along with an image of the Nakuru National Park (Figure 5.2). They are reproduced as follows:
Figure 5.1: Orthographic Perspective of the Study Area

In the image, Nakuru Township appears in a gray color northwest of Lake Nakuru. The Nakuru National Park surrounds the lake. The Nakuru region is one of the most important agricultural areas in Kenya today. Established originally as a farming settlement, Nakuru has recently acquired an important role as service and administrative center for the neighboring township. It also has a growing industrial sector geared towards the processing of local agricultural produce such as wheat.
Figure 5.2: The Lake Nakuru National Park Extent

5.2 DATA USED FOR THE CASE STUDY

Basic data on Nakuru National Park that was used in this researcher’s case study came from the United Nations Environment Program/Global Resources Information Database (UNEP/GRID) in collaboration with Kenyan Government.

The available data used are as follows:
Nakuru National Park raster image - derived from LANDSAT™ imagery.

A digital elevation model (DEM).

A vector file of roads, called ROADS.

The TM imagery dates from February 1990, and has a resolution of 30 meters. The DEM was developed from a 1:100,000-scale map with a 100-foot contour interval. The roads were digitized from a 1:25,000 scale map and generalized.

5.3 **IDRISI**

The software chosen by this researcher for the AHP case for the Nakuru National Park case study is IDRISI. The software is named for an ancient North African cartographer, Abi Jafar Ibn al-Idrisi. Born in 1099 A.D. in a Spanish colony on the North African coast (actual Morocco), educated at the University of Cordoba in Spain, and well traveled all over the then-known world, Idrisi was a cartographer and geographer of major significance of the Middle Ages.

![IDRISI for Windows](image)

IDRISI is a geographic and image processing software system developed, as a non-profit project, by the Graduate School of Geography at Clark University, and is designed to provide professional-level geographic research tools.

Figure 5.3: IDRISI for Windows

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IDRISI for Windows consists of a main interface program (the one with the menu and toolbar system) and a collection of over 150 program modules that provide facilities for the input, display and analysis of geographic data. It also offers extended capabilities for input, display and database query of geographic data and is the vehicle for all new analytical developments. The geographic data is described in the form of map layers – elementary map components that describe a single theme. Examples of map layers include road layer, elevation layer, soil-type layer, etc. The analysis performed by IDRISI acts on map layers and, for display, map layers may be brought together into a map composition.

IDRISI is best known for its decision-support tools. Foremost among these are multi-criteria and multi-objective decision-making processes that include a procedure for weighing criteria, fuzzy standardization, and an extensive set of criteria-aggregation procedures. It also provides tools for uncertainty management, including error propagation through Monte Carlo simulation. This technique involves the use of simulation to estimate the effects of random variables on systems – hence the analogy with the casino tables at Monte Carlo (Eastman et al., 1993).

To estimate the effects of error on the analysis, the analysis is performed twice, once in the normal fashion and then a second time with simulated error built into the input data. The two results are then compared, and the only reason they differ is because of the simulated error that was introduced. A histogram of the difference between the two images is used to arrive at a characterization of the error.
The way in which the software components mentioned above are combined is one aspect of how Geographic Information Systems vary. However, an even more fundamental distinction is how they represent map data in digital form.

A Geographic Information System stores two types of data that are found on a map – the geographic definitions of earth surface features and the attributes or qualities that those features possess. Not all systems use the same logic for achieving this. Nearly all, however, use one or a combination of both of the fundamental map-layers representation techniques: vector and raster.

- **Vector Layers** are very useful in defining landscape features like roads, property boundaries, administrative districts, etc. They are defined by a series a points that, when joined with straight lines, form the graphic representation of the feature. The points themselves are encoded with a pair of numbers giving the X and Y coordinates in systems such as latitude/longitude or Universal Transverse Mercator grid coordinates. The attributes of features are then stored with a traditional database management (DBMS) software program.

- **Raster Layers** describe a region of space by means of a fine matrix of cells (pixels). These cells contain numeric values that express the condition or attribute of the earth’s surface at that point, representing either a feature identifier, a qualitative attribute code or a quantitative attribute value. Raster layers are usually describing spatially continuous data such as elevation, temperature, and rainfall data.

Even though IDRISI for Windows is suitable for both raster and vector layers, analysis is oriented towards the use of the raster ones. As a result, IDRISI for Windows is commonly known as a raster-based software. Anyway, IDRISI for Windows offers

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capabilities for raster-to-vector and vice-versa, allowing vector layers to be incorporated in the analysis very easily.

While decision support is one of the most important functions of a Geographical Information System, tools designed especially for this are relatively few in most GIS software. However, IDRISI for Windows includes several modules specifically developed to aid in the resource allocation decision-making process. These include modules that incorporate error into the process, help in the construction of multi-criteria suitability maps, and address allocation decisions when there are multiple objectives involved. Used in conjunction with the other components of the system, these modules provide a powerful tool for the resource allocation decision-makers.

Among the other reasons for the researcher in choosing IDRISI for Windows for first part of the case study, the most important is the ability to perform Analytic Hierarchy Process analysis. The others are, compatibility with the data provided and its availability to The Ohio State University.

5.4 CASE STUDY PART I – DISCUSSION

The problem the researcher will examine is that of land use development planning, consisting of a complementary-objectives allocation of zoning lands for industrial use, and for residential use.

The agro-based industries in the Nakuru area are fairly low-impact industries that are best situated near residential areas in order to take advantage of available labor at minimal cost, therefore we will look for the areas that are suitable for both industrial and
residential use. In other words the best 4,000 hectares are going to be allocated for both industrial and residential uses, solving a clear case of combined uses.

It should be noted that this case is being undertaken to explore GIS as a decision-making tool and not to come up with a definitive answer as to land usage in Nakuru National Park.

**Problem Statement**

The problem of developing the planning-zone map falls in the realm of multi-objective/multi-criteria decision problems. In our case the scope being to facilitate land use development planning for industrial and residential, we have two complementary objectives.

Taking them separately as Single-Objective/Multi-Criteria Evaluation, the evaluation of each of these objectives can be seen as to require a number of criteria. Both suitability maps the researcher wants to create seem to require the same suitability factors such *distance from town, distance from roads, slope gradients* and *distance from park*.

**Structuring The Decision Rule**

The first step in solving this land allocation problem is to structure a rule that will allow a decision about which areas to include as part of the best 4,000 hectares of industrial and residential land.

Decision rules typically involve a process for the combination of one or more criteria (factors and constraints) into a composite index and a subsequent procedure (in the form of a choice function or heuristic) for comparing alternatives on the basis of the composite index.
Identifying the Criteria

Identifying relevant criteria can be approached by considering site characteristics and situational conditions. *Site characteristics* refer to surface and near surface qualities that the land must posses for the land use activity being proposed. Site characteristics might include such factors as slope of the land, soil characteristics, land-cover types, temperature, rainfall, and other criteria that are derived mainly from the physical qualities of land at each site. *Situational conditions* comprise relationships between each site and the surrounding areas. Examples here might include issues such as proximity to roads and also proximity to town, the nature of adjacent land usage, and so on.

Multi-Criteria Evaluation

After research had been done, playing the role of a land planner, considering the site characteristics and situational conditions for industry and residential development, the researcher’s consideration was given to the following factors:

- **Proximity to Roads.** The need of transporting raw products and finished materials, and also being near to an existing road, taking in account that road construction is expensive, would thus be quite advantageous.

- **Proximity to Town.** The source of much of the labor for industry would be Nakuru town, as well as such supporting services as banks and government offices. While not exactly a major factor, the researcher felt that proximity to town would be a factor that should be considered in the analysis.
- **Slope Gradient.** Most industries find slope to be a disadvantageous attribute. Steeper slopes increase construction costs, limit maximum floor areas, and contribute to erosion during construction and subsequent use.

- **Distance from Lake Nakuru National Park.** The economy of the entire area is very much dependent upon tourism associated with the park. It is therefore in the best interest of all to help preserve the park as a wildlife refuge and as a tourist attraction, hence the industry and residential areas should be located as far away as possible from the park, for reasons of air and water pollution, noise disturbance, contributions to the lake siltation and the like.

  In addition to the above factors, this researcher found a significant constraint to be considered in the zoning of lands for the industrial and residential use:

- **Park Constraint.** Since the park is a designated National Park, no development can be considered within its boundaries.

**Combining the Criteria**

Since we have continuous factors in addition to Boolean constraints in this problem, our procedure for combining the criteria, will be in the form of a weighted linear combination (Voogd, 1983, p.120):

\[ S = \sum w_i \cdot x_i \cdot \Pi c_j \]

where

- \( S \) = suitability to the objective being considered
- \( x_i \) = criterion score of factor \( i \)
- \( w_i \) = weight of factor \( i \)
- \( c_j \) = criterion score (0/1) of constraint \( j \)
- \( \Pi \) = product operator

The result of this process will be a quantitative suitability map in which each location is rated for its suitability for industrial use as well as for residential use.
Choice Procedure Implementation

Since we want the area ultimately chosen to be the best possible area for that purpose, the simplest possible procedure is to use a choice heuristic such that we rank order the raster cells in terms of their suitability for industrial and residential use and then take however many of the best cells as are required to make up 4,000 hectares.

That is equivalent to the following choice function:

$$\text{Max} \left( \sum S_k \right) \quad \text{where} \quad S = \text{suitability of cell } k$$

With the constraint that:

$$\sum \text{Area} \left(k \right) = 4,000 \text{ hectares.}$$

Creation of the Factor Maps

The development of the factor maps will usually encounter two or three distinct steps. In the first step, the factor map will be created using standard IDRISI modules, using the available data. In the second step, the values in the map will be standardized to a specific range. In the third step, whenever necessary, values will be inverted to assure that high values on the map correspond to areas more suitable to the objective under consideration. However, the weighted linear combination (WLC) procedure that will be used here requires that each of factor map to be standardized to a consistent range of byte binary integers (e.g., 0 – 255). In addition, it requires that each be constructed such that higher values indicate areas that are more suitable on that factor.
Proximity to Roads Factor Map

This image (ROADDIST) was created by rasterizing the ROADS vector file using the module LINERAS which converts vector lines to their raster equivalents, and then running IDRISI's module DISTANCE (used to measure the Euclidean line distance between each cell and the nearest of a set of target features). Distances were subsequently converted to kilometers as indicated in the documentation file. This image will serve as the basis for the road proximity factor. We will name it ROADDIST.

To standardize the distance values, which translate in making them fall in a consistent range of byte binary integers (i.e. 0 – 255 in this case), the STRETCH module is used. The problem with this image now is that the more desirable areas are near the roads, but they have the lowest values. As we stated before, one of the requirements it is that each factor map to be constructed such that higher values indicate areas that are more suitable on that factor. Therefore we will need to reverse the image.

To reverse the criterion scores, INITIAL module is used, creating a new byte binary image with values from 0 to 255 (256 levels), and adopting the spatial parameters of ROADDIST. After initializing the image, the OVERLAY module with SUBTRACT option is used to produce a new image from the data of two input images, called ROADFAC. Using the DISPLAY LAUNCHER (the module that allows us to see the results by opening display window) we can visualize the first factor map, which represents proximity to roads, ROADFAC (Figure 5.4).
Figure 5.4: Proximity to Roads Factor Map

**Proximity to Town Factor Map**

This second image was created by using the COST module using the COSTGROW algorithm. Cost distances were calculated from the town boundary through a friction map in which the park was established as an absolute barrier (-1), roads were given a base friction of 1 and areas off road were given a friction of 10. Thus the town is essentially closer if one is near a road than one is far from a road. Cost distances are expressed in cell equivalents. Thus for example, if a cell has a cost distance of 100, this would indicate that it costs the same (in time, effort or money) to get to the town as it
would to travel through 100 cells along a road. This image can serve as the basis for the proximity to town factor. We will name it COSTDIST.

Following the procedures indicated above, STRETCH module was used again in order to create a standardized map out of COSTDIST, indicating a simple linear stretch between minimum and maximum and a total of 256 levels (0-255) in which values are standardized to a range determined by the extreme values that exist within the study area. Again, the order of the values in this standardized map is reversed (each factor map to be constructed such that higher values indicate areas that are more suitable on that factor). Therefore in needing to reverse the image, OVERLAY module was used in order to subtract the two intermediate maps created previously, and along with the DISPLAY option, the final proximity to town factor map, called TOWNFAC was created (Figure 5.5). The park shows up as being desirable in this map. This is an artifact of the processing which needn’t concern us at this stage, since the park constraint will mask out any values in the park at the end.
Figure 5.5: Proximity to Town Factor Map

**Slope Gradient Factor Map**

This third image was created by running SURFACE on a digital elevation model (DEM) for the Nakuru area. Slope gradients are expressed in percents. This is clearly the map required for the slope factor. We will call it SLOPE. In order to standardize this map to a 0 – 255 byte binary range, we start by running STRETCH to create a new intermediary map, TMP from the existing one, SLOPE, indicating just a linear stretch between the minimum and maximum, with 256 (0-255) levels.
Once again, the order of the values in this standardized map is reversed, therefore we make use of the OVERLAY module to subtract the two intermediate images created, the result being the final slope factor map, SLOPEFAC (Figure 5.6).

Figure 5.6: Slope Gradient Factor Map
**Distance from Park Factor Map**

By running DISTANCE on the PARK image, we created this fourth image. It was then recalibrated using SCALAR to convert distances in kilometers. We will name it PARKDIST.

Now we just have to standardize this, by running STRETCH module to create a new map named PARKFAC (Figure 5.7) from the existing PARKDIST. By indicating a simple linear stretch between the minimum and maximum, within the 256 levels (0 – 255), and using DISPLAY LAUNCHER, we are getting the final distance from the park factor map. This time we don’t need to reverse this one since in this case the most suitable pixels are furthest from the Park.

![Distance from Park Factor Map](image)

Figure 5.7: Distance from Park Factor Map
The Park Constraint Map

In this case, we need to create a Boolean image such that areas within the park are given a value of zero, and those outside the park are given a value of one, by running the module RECLASS (RECLASS classifies or reclassifies the data stored in images or attribute values files into new integer categories; classification or reclassification is by equal intervals division of the data range, or by the application of user-defined limits). In order to reclassify the map called PARK, which is readily available for use, I used the user-defined classification and assigned a new value of 0 to the old values from 0 to 1 and a new value of 1 to the old values from 1 to 999. The newly created map was called PARKMASK (figure 5.8):

Fig 5.8: The Park Constraint Map
**Calculation of the Factor Weights**

Having the criteria (factors and the constraint) maps been created and standardized, next step is to develop a set of weights to establish these maps' relative importance to the objective under consideration. In doing that, these weights should be real numbers that sum to 1.0. The first step in doing that is to create a pairwise comparison matrix in which each factor is evaluated for its importance relative to every other factor in determining the suitability of land for industry. The factor maps will be then multiplied by their weights and subsequently added together. Since the weights sum is 1.0 and all the factor maps have a standardized 0 – 255 range, the final weighted linear combination will be having a range of 0 – 255. The last step will involve the multiplication of the suitability map with the constraint factor in order to zero-out all excluded areas.

IDRISI's module WEIGHT which is going to be used in pursuing this goal, is built up on a very original technique for developing the weights, a technique developed by Thomas L. Saaty (1977) as part of the process known as Analytic Hierarchy Process (see Chapter 3).

Creation of this comparison matrix can be done by an individual or by a decision-making group. In the latter case, the GIS analyst acts as a focus group leader in eliciting the opinions of group members, regarding the relative importance of the factors involved. In making this, a 9-point ratio-scale is used (Figure 5.9):
<table>
<thead>
<tr>
<th>1/9</th>
<th>1/7</th>
<th>1/5</th>
<th>1/3</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>extremely</td>
<td>very strongly</td>
<td>strongly</td>
<td>moderately</td>
<td>equally</td>
<td>moderately</td>
<td>strongly</td>
<td>very strongly</td>
<td>extremely</td>
</tr>
</tbody>
</table>

less important  more important

Figure 5.9: The AHP’s Fundamental Scale

The scale is continuous and thus allows ratings of 4.7, 5.43 and so on. In addition in comparing rows to columns in the pairwise comparison matrix, if a factor is seen to be less important rather than more important than the other, the inverse of the rating is given. For example, if a factor is seen to be very strongly less important than the other, it would be given a rating of 1/7. Fractional ratings are permitted with reciprocal ratings as well, thus to have ratings of 1/3.5 or 1/7.8 and so on.

A pairwise comparison matrix is created by setting out one row and one column for each factor in the problem, in order to provide a systematic procedure for comparison. The group involved (researcher) in the decision making process provides a rating for each of the cells in this matrix. Since the matrix is ‘symmetrical’ ratings can be provided for one half of the matrix and then inferred for the other half, so only the lower triangular half actually needs to be filled in. Since each factor is of equal importance of itself, the diagonal is filled with 1’s. The judgment of the relative importance between two factors is made in accordance with a statement such as:
"Relative to the row factor, how would you judge the importance of the column factor?"

<table>
<thead>
<tr>
<th></th>
<th>ROADFAC</th>
<th>TOWNFAC</th>
<th>SLOPEFAC</th>
<th>PARKFAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROADFAC</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOWNFAC</td>
<td></td>
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<td>PARKFAC</td>
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<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 5.10: The Pairwise Comparison Matrix

Because this case study is being done for the purpose of looking at GIS as a decision making tool, the necessary weights needed in order to fill up the pairwise comparison matrix (figure 5.11), will be assigned by the researcher. In doing that we have to consider economic and efficiency factors.

Roads are very important because of the need to transport raw products and finished materials. Road construction is expensive and being near to an existing road would be quite advantageous. Being close to Nakuru town is advantageous because the source of the labor for industry, as much as services and finished materials, as well as services as banks and government offices. It is very clear that without existing roads everything would become very expensive, but being a little bit far from the town wouldn’t be such an inconvenience in the case of existing roads. Such considerations led
the researcher to rate proximity to roads criteria as moderately more important than proximity to town, and so on.

As indicated above, only the lower triangular half of the matrix has to be filled up since the matrix is symmetric. Road factor is moderately more important than town factor, equally important as slope factor, and moderately more important than park factor. Slope factor is in between moderately and strongly more important than town factor and in between equally and moderately more important than the park factor.

<table>
<thead>
<tr>
<th></th>
<th>ROADFAC</th>
<th>TOWNFAC</th>
<th>SLOPEFAC</th>
<th>PARKFAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROADFAC</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOWNFAC</td>
<td>1/3</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLOPEFAC</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>PARKFAC</td>
<td>1/3</td>
<td>2</td>
<td>1/2</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 5.11: The Filled Pairwise Comparison Matrix for Industry

Once the matrix has been completed, a pairwise comparison file is created to record the results, after which IDRISI's module WEIGHT is used to estimate the weights.

This is possible by running a module called EDIT and choosing to create a pairwise comparison file, which has to be created in the format shown below (Figure 5.12):
Figure 5.12: The Outcome of Pairwise Comparison Matrix for Industry

The first line indicates the number of factors, after which the factors are listed on successive lines. Then the lower triangular half of the matrix is entered, one row at a time, with one space between column entries.

The WEIGHT module is then run to estimate the weights, and by running the pairwise comparison file, we get the best-fit weights for each factor (in the form of a eigenvector) and an indication of the consistency of the judgments.
Saaty (1980) stated that the consistency ratio (C.R.) is the ratio of the consistency index (C.I.) or the "closeness to consistency" to the average random index (R.I.) for the same order matrix. A consistency ratio of 0.10 or less is considered acceptable.

\[ \text{C.I.} = \frac{(\lambda_{\text{max}} - n)}{(n - 1)} \quad \text{where} \quad \lambda_{\text{max}} = \text{the principal eigenvalue} \]

\[ n = \text{the number of activities in the matrix} \]

The closer \( \lambda_{\text{max}} \) is to \( n \), the more consistent is the result.

**R.I.** is the consistency index of a randomly generated reciprocal matrix from the scale 1 to 9, with reciprocal forced. This was statistically determined by researchers at Oak Ridge National Laboratory, who generated an average R.I. for matrices of order 1-15 using a sample size of 100. One would expect the R.I. to increase as the order of the matrix increases. The following table (Figure 5.13) gives the order of the matrix (first row) and the average R.I. (second row) determined as described above.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<th>7</th>
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<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
<td>1.51</td>
<td>1.48</td>
<td>1.56</td>
<td>1.57</td>
<td>1.59</td>
</tr>
</tbody>
</table>

**Figure 5.13:** Table of Consistency Ratios for Different Matrix Orders
The consistency ratio in our case is equal to 0.02, which is acceptable as shown below. If the consistency ratio is greater than 0.1, then our matrix is not adequately consistent, and we need to consider reevaluating the matrix. Also it is necessary that the weights sum to 1.

The eigenvector of weights is (Figure 5.14):

- ROADFAC: 0.3770
- TOWNFAC: 0.0978
- SLOPEFAC: 0.3605
- PARKFAC: 0.1647

Consistency Ratio = 0.02
Consistency is acceptable.
Σ = 1

---

*Figure 5.14: The Outcome of the Eigenvector of Weights for Industrial*

---

**Multi-Criteria Evaluation (MCE) for Industrial Use**

Standard GIS arithmetic and logic operations can be used to perform the *weighted linear combination*, as outlined above. However, IDRISI contains a module named MCE that can simplify and speed up this process. The procedure starts by multiplying each of the factors (ROADFAC, TOWNFAC, SLOPEFAC, and PARKFAC) by the respective weight obtained using the WEIGHT module mentioned above, and then adding the results. The weighted linear combination will be then undertaken followed by a multiplication of the result by the constraint (PARKMASK), the image obtained and visualized with DISPLAY, the resulting map for the industrial suitability map use being called INDSUIT (Figure 5.15):
Figure 5.15: The Industrial Suitability Map

**Multi-Criteria Evaluation (MCE) for Residential Use**

We can now start with the second objective. The agro-based industries in the Nakuru area are fairly low-impact industries that are best situated near residential areas in order to take advantage of available labor at minimal cost. We will thus look over the areas that are suitable for *residential* use. In order to do so we need to create an independent suitability map for our second objective, *residential use*. It was decided that
the same four factors (ROADFAC, TOWNFAC, SLOPEFAC and PARKFAC) and one constraint (PARKMASK) would be appropriate for determining the suitability for residential use. In addition, it was decided that a total of 4,000 hectares was to be allocated to this combined urban use. Following a similar procedure to that mentioned earlier, the pairwise comparison matrix looks as follows (Figure 5.16):

<table>
<thead>
<tr>
<th></th>
<th>ROADFAC</th>
<th>TOWNFAC</th>
<th>SLOPEFAC</th>
<th>PARKFAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROADFAC</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOWNFAC</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLOPEFAC</td>
<td>9</td>
<td>8</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>PARKFAC</td>
<td>7</td>
<td>6</td>
<td>1/3</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 5.16: The Filled Pairwise Comparison Matrix for Residential

Since all of the factor and constraint maps have been prepared, we can proceed directly to the Multi - Criteria Evaluation for residential suitability. The eigenvector of weights is:

ROADFAC : 0.2958
TOWNFAC : 0.5857
SLOPEFAC : 0.0771
PARKFAC : 0.0415
Consistency Ratio = 0.09
Consistency is acceptable.
Σ = 1

Figure 5.17: The Outcome of the Eigenvector of Weights for Residential

The same MCE procedures (as for industrial use), are then used to produce the 
residential suitability map, RESSUIT (Figure 5.18):
5.5 **MULTI-CRITERIA / MULTI-OBJECTIVE DECISION-MAKING**

*Multi-Objective Decision Procedures*

The first consideration with multi-objective problems is whether the objectives are conflicting or not. If they don’t we called them complementary, and a hierarchical extension of the MCE procedure can be used. However, if they do conflict, either a prioritized solution must be used, or the conflict will need to be solved by some form of compromise solution using IDRISI’s module MOLA.

*Our aim is to develop a zoning map that is suitable both for industrial and residential uses, by allocating a total of 4,000 hectares for this combined use.*
In the case study, however, we do see the two objectives as complementary, because they are not competing for the same land and resources. With complementary objectives, the concern is to find regions that satisfy all objectives simultaneously to the best degree possible. Each of these objectives was previously viewed as a separate multi-criteria/single-objective problem. However, to find areas that serve both of these objectives, we need to extend the analysis to another hierarchical level (Saaty, 1980). In this case we consider the suitability maps resulted from the separate multi-criteria evaluations as if they were factors to the next level of analysis. The objectives can then be assigned weights and combined using the MCE procedure. As long as the weights add to 1 the MCE procedure can be used to solve the multi-objective problem with complementary objectives.

*Multi-Criteria Evaluation (MCE) for Urban Use*

We have now two suitability maps – one for industry (INDSUIT) and one for residential (RESSUIT). We now need to combine these to find areas that are best suited to both. To do so we will use the same procedure as we have so far with the MCE module, except that our suitability maps will now become the new factors in this next level of analysis. However, to do so, we have to follow each of the steps usually associated with this procedure: standardization, derivation of weights, and linear combination. Since the suitability maps have the same inherent range (0-255) it is easy to believe that they are measured on a comparable basis, but since each of these suitability maps have been created entirely independently of one another, hence internally consistent, there is no reason to believe that a particular level of suitability has the same
meaning on both suitability maps. Since in the case study the distribution is not normal, a non-parametric procedure that can be used is the one called histogram equalization. We could do this in two different ways – either by means of the histogram equalization procedure in STRETCH module, or by means of RANK both leading us to the same result. We are going to use STRETCH since it can produce a byte binary output as is required in the second stage run of MCE. Running STRETCH to modify INDSUIT to produce INDHEQ, and again to create RESHEQ from RESSUIT, we have now two standardized suitability maps (INDHEQ) and (RESHEQ) for which we have to derive a set of weights. With many objectives, we can use the pairwise comparison procedure along with the WEIGHT to help the process. In the case study we have just two objectives, and this can be done directly through discussions with the decision group. The researcher decided to give weights 0.60 and 0.40 to industry and residential, respectively, suggesting that areas judged to be suitable for urbanization will be those that slightly favor industrial needs over those of residential.

The procedure starts with MCE (Multi-Criteria Evaluation) indicating there will be one constraint (PARKMASK) and two factors (INDHEQ) and (RESHEQ), with the weights 0.6 and 0.4 respectively. The result is called URBSUIT. To complete the decision rule, we now need to apply the choice heuristic that will allow us to select the best 4,000 hectares for the urban use. This involves rank ordering the cells in terms of their suitability for both industrial and residential use and selecting the best 4,000 hectares worth of cells. Therefore, the next step is running RANK to create URBRANK from URBSUIT, with the purpose of creating a basis for choosing the most highly ranked
areas. Since in this image cells are 30 x 30 meters, it means that each cell is about 0.09 hectares in size, hence we have to select the best 44,444 (4,000/0.09) cells.

The last step is running RECLASS module in order to reclassify URBRANK and to create URBAN (Figure 5.19), along with overlaying the vector file ROADS. This is the final result that combines the complementary objectives of industrial and residential lands into a single allocation for urban uses.

Figure 5.19: Final Allocation Map for Urban Use
PART II: THE ANALYTIC NETWORK PROCESS APPROACH

A SINGLE CONTROL CRITERION: LONG TERM ECONOMIC BENEFITS

5.6 PROBLEM STATEMENT

In the second part of the Nakuru case study we want to see what is the economic impact of the land allocation problem solved in the first part by creating a model that would predict the Long Term Economic Benefits for Nakuru area. We decided that the best way we could handle these considerations is by modeling the problem as a network. This is going to be done with the help of the ANP’s software Super-Decisions. The objective of the decision is to make the investors aware about the mid-term and long-term benefits of the three main areas of economic impact of Nakuru, Industrial Development, Residential Development, and Lake Nakuru National Park, for investing in accordance to their priority ranking.

As we stated before, network models do not have levels such as goal, objectives, and alternatives. Instead the elements (or nodes) in a network model are grouped into clusters (or components), such as Alternatives cluster, Distance from Park cluster, Proximity to Roads cluster, Proximity to Town cluster, and Slope Gradient cluster. Each of these clusters (components) contains elements (nodes) as follows (Figure 5.20):

ALTERNATIVES: Industrial, Residential and Park.

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DISTANCE FROM PARK: Tourism and Environmental Pollution.

PROXIMITY TO ROADS: Existing Roads and Transportation.

PROXIMITY TO TOWN: Labor and Service.

SLOPE GRADIENT: Construction Costs, Erosion, and Floor Areas.

Figure 5.20: The Network’s Clusters, Nodes, and their Dependencies

What we are looking for in this case is to capture the complex interaction of components and elements with respect to the control criterion, which translates into
finding out the overall synthesized priorities for all the elements, and in particular for those that interests us, the Alternatives, which are: *Industrial, Residential, and Park*.

In order to achieve this, some steps like organizing the criteria, prioritize them in the framework of a network, performing comparisons, synthesizing for getting the priorities, deriving the influence of components in the network with respect to the criterion, weighting the resulting influences, adding them in order to get the overall influence, must be followed.

In this case *the Control Criterion*, Long Term Economic Benefits, does not connect directly to the structure but “induces” comparisons in the network. This is the case where the Control Criterion is called *comparison – inducing*. This is also the case of an *irreducible primitive matrix*, as we’ll see later on.

The question for the Alternatives in this case is: with respect to the *control criterion*, “which of the alternatives is more important and how much more”?

The components in the network represent five major factors that impact the control criterion, Long Term Economic Benefits, ranked in the order of importance:

The *Alternatives* component is the most important and consists of three elements, Industrial, Residential and Park. This is considered the most important factor with regard to the Control Criterion, since the Economy of Nakuru will be expected to flourish based on Industrial Development, Residential Development and as we already know, on the benefits associated with the Lake Nakuru National Park, called from now on Industrial, Residential and Park.
Distance From Lake Nakuru National Park is the second most important component of the network, consisting of two elements: Tourism and Environmental Pollution. The economy of the entire area is very much dependent upon tourism associated with the park. It is therefore in the best interest of all to help preserve the park as a wildlife refuge and as a tourist attraction, hence the industrial and residential areas should be located as far away as possible from the park, for reasons of air and water pollution, noise disturbance, contributions to lake siltation and the like.

Proximity to Roads is the third most important component in the network, consisting of two elements: Existing Roads and Transportation. The need for transporting raw products and finished materials as well as common transportation, being also near to an existing road taking in account that road construction is expensive, would thus be quite advantageous.

Proximity to Town ranked fourth most important component (cluster) in the network, consisting of two elements (nodes): Labor and Services. The source for much of the labor for industry, as well as for supporting services as banks and government offices, would be Nakuru town. While not exactly a major factor, the researcher felt that proximity to town would be a factor that should be considered in the analysis.

The last and the least is Slope Gradient component (cluster), with three elements (nodes): Construction Costs, Erosion and Floor Areas. Most industries find slope to be a disadvantageous attribute. Steeper slopes increase construction costs, limit maximum floor areas, and contribute to erosion during construction and subsequent use.
5.7 DEPENDENCIES IN THE NETWORK

As we said before, a component has outer dependence when its elements are linked to the elements in another cluster, and also has inner dependence when elements are linked to other elements in their own cluster.

As figure 5.20 shows, all of the clusters have inner dependence and also outer dependence. More than that, they have reciprocal outer dependence (feedback or cycle), except clusters 2: “Distance from Park” and 5: “Slope Gradient”, for which the actual researcher didn’t find any kind of relation, respectively between their nodes, which means that the nodes Tourism, and Environmental Pollution (Cluster 2) and Construction Costs, Erosion and Floor Areas (Cluster 5) are not directly connected, hence no outer dependence between clusters two and five.

The fact they don’t have direct influence on each other does not mean that they do not have indirect one. For example both of them are having feedback with the Cluster 1 “Alternatives” so this is the clear case of indirect influence through the Cluster 1. The connection between nodes is shown in the Appendix, pages 114-117, and is exemplified in four handouts. Each node dependence is exemplified in a “FROM” and “TO” form, meaning all the connections from a node to the other nodes and all the connections of the other nodes connected to that node.

The nodes belonging to the Cluster 1 “Alternatives” are connected in a feedback relation with all the other nodes.

The nodes belonging to the Cluster 2 “Distance from Park” are connected in a feedback relation with all the other nodes, except the nodes of Cluster 5 “Slope Gradient”. As
specified previously there is no connection between the Cluster 2 and Cluster 5, hence any direct connection between nodes.

The nodes belonging to the Cluster 3 “Proximity to Roads” are connected in a feedback relation with all the other nodes, except the Node 2 Erosion and Node 3 Floor Areas of the Cluster 5 “Slope Gradient”.

The Node 1 Labor of the Cluster 4 “Proximity to Town” is connected with feedback with all the other nodes except Node 2 Erosion and Node 3 Floor Areas of the Cluster 5 “Slope Gradient”. As for the Node 2 Services belonging to the Cluster 4 “Proximity to Town”, is connected with feedback with every other node but all the nodes of Cluster 5 “Slope Gradient”.

The nodes belonging to the Cluster 5 “Slope Gradient” are connected with feedback only with few nodes. Node 1 Construction Costs with all but the both nodes of Cluster 2 “Distance from Park” and Node 2 Services of Cluster 4 “Proximity to Town”. The Nodes 2 Erosion and 3 Floor Area are connected just with the nodes of Cluster 1 “Alternatives”. The creation of the network and their dependencies has been done with the Super Decision software, with the commands DESIGN CLUSTERS, DESIGN NODES, NODE CONNECTION FROM, and NODE CONNECTION TO.

5.8 THE PAIRWISE COMPARISON OF CLUSTERS AND NODES

The next step, after figuring out the dependencies among elements and linking them in the network, is to start eliciting judgments on the clusters and elements, which leads to the pairwise comparison of clusters and nodes. This is going to be done with the commands CLUSTER COMPARISON and NODE COMPARISON from the menu.
ASSESS/COMPARE, in one of the four modes: Graphic, Verbal, Matrix and Questionnaire. The researcher used first the questionnaire for a better visualization of the scale comparison, and for doing that the 1-9 AHP’s fundamental scale was used in order to compare clusters and nodes.

Starting with the cluster comparisons, continuing with node comparisons, after completing all the questionnaires, the third option of doing the comparisons, the arrangement of the comparisons under the form of a matrix was necessary. The generic question used for comparing two clusters or two nodes in the questionnaire was:

"With respect to the Long Term Economic Benefits, and on a 1-9 scale, which one of these two clusters or nodes has greater influence with respect to the aforementioned criterion"?

All the questionnaires are shown in the Appendix, pages 118-125, in the graphical form of handouts, and they are arranged in the order of their comparison, starting with Cluster 1 and ending with Cluster 5.

5.9 THE MATRIX OF PAIRWISE COMPARISON AND THE PRIORITIES

Having all the comparisons made between nodes and clusters put under the form of a matrix of pairwise comparison, next step was achieving the eigenvalue \( \lambda_{\text{max}} \), the priority vector (eigenvector) \( W \) and the consistency ratio for each matrix.

The computation of the eigenvalue \( \lambda_{\text{max}} \) and the priority vector (eigenvector) \( W \) are obtained from the equation: \( A \cdot w = \lambda_{\text{max}} \cdot w \), known as the eigenvalue problem.
The consistency ratio (C.R.) is defined by Saaty (1980) like the ratio of the consistency index (C.I.) or the "closeness to consistency" to the average random index (R.I.) for the same order matrix. A consistency ratio of 0.10 or less is considered acceptable.

The pairwise comparison matrices as well as the priority vectors and their consistency ratios are shown altogether in the Appendix, from pages 126-133 in the order of their comparison.

5.10 THE SUPERMATRICES

After the calculation of the vector priorities from the paired comparison matrices, the next step is creating the Supermatrix, in which the priorities are arranged in partial column entries, some of them having also some blocks of zeros, which are indicating no interaction between those nodes or clusters. As we saw in the Chapter 3, p. 50, the Supermatrix that we have now, called the Unweighted Supermatrix and shown in the Appendix (Table 5.1, page 109), has the columns summing to more than one, which means is not normalized, so we can't derive the limit priorities of influence from it. In order to do so it must be first transformed to one whose columns sums to unity, called a stochastic matrix.

The clusters were weighted in separate pairwise comparison matrices as to their impact on each component. The resulting priorities are shown in the Appendix (Table 5.2, page 110). These priorities are then used to weight the corresponding blocks of the Unweighted Supermatrix, yielding the Weighted Supermatrix, whose columns this time sum to unity as shown in the Appendix (Table 5.3, p. 111). The entries of the Weighted Supermatrix itself give the direct influence of any element on any other element, so what
we really want right now is to capture the transmission of influence along all possible paths of the Weighted Supermatrix. In order to do so we raise it to limiting powers as given in the Appendix (Table 5.4, p. 112) and then normalized by blocks, yielding the *Limit Supermatrix* (Table 5.5, p. 113) in the Appendix. Since the limit matrix has no zeros, some powers of the weighted supermatrix has no zeros, and thus the supermatrix itself is primitive, which translates to the fact that the weighted supermatrix is *irreducible* (the principal eigenvalue \( \lambda_{\text{max}} \) is simple and therefore occurs only once) and there are no other roots of \( \lambda_{\text{max}} \) whose moduli are equal to one.

The Limit Supermatrix has the same form as the Weighted Supermatrix, but all the columns are the same, hence convergent. To obtain the final priorities of all the elements in the matrix, we have to normalize each block by cluster.

It is the *limit supermatrix* that predicts the Long Term Economic Benefits for the Alternatives, which are the three land categories chosen: *Industrial, Residential and Park*. Based on the outcome, we should be able to use the dominant factors in the model in taking economic benefit. Sensitivity analysis can be performed to plan various strategies.

The participation of the Alternatives to the Long-Term Economic Benefits as determined by the supermatrix model is as follows (Figure 5.22):

- **Industrial Land Use**: 43.80%
- **Residential Land Use**: 33.06%
- **Park**: 23.14%
Figure 5.21: The Overall Synthesized Priorities for the Alternatives

This procedure completes the process. At a basic practical level, we have successfully created a Decision-Making *predictive model* that shows us the impact that allocated land use categories will have on the Nakuru Area.

The investors will now know how to invest in the area, and that will be in accordance with the priority ranking of the overall synthesized priorities of the alternatives.
CHAPTER 6

COMPARISON AND DISCUSSION

The AHP is a theory that depends on the values and judgments of individuals and groups (Saaty, 2001).

The ANP is a generalization of the AHP, which replaces hierarchies with networks. In both approaches to decision-making, judgments are brought together in an organized manner to derive priorities. Developing a 1 to 9 scale to represent the judgments, through which the decision comes out the best, a group of alternatives is prioritized and resources are allocated in proportion to these priorities.

The ANP is a theory of measurement generally applied to the dominance of influence among several stakeholders or alternatives with respect to an attribute or a criterion (Saaty, 2001).

A generic question would arise in everybody's mind in regard to these two methods:

"What is the difference between an influence network and an influence hierarchy, and how do we know which structure to use for a decision problem?"

In general, writes Saaty (2001), hierarchies concern the distribution of a property (the goal) among the elements being compared, to judge which one influences or is
influenced more or has a greater amount of that property (goal). Networks concern the distribution of the influence of elements on some element with respect to a given property (criterion).

This translates in the first part of our case study (AHP), by establishing the goal of which is the land allocation of the best 4,000 hectares for the combined urban use, with the criteria consisting of the four factors and one constraint, and the alternatives represented by the complementary land allocation (industrial and residential). In other words the goal is distributed through the criteria, establishing the best alternative for the urban use.

For the second part of our case study (ANP), the overall influence of the elements, contained in the components, is “measured” with respect to the comparison-inducing control criterion “Long Term Economic Benefits” for the Nakuru area, with the aim of prioritization of alternatives (industrial, residential and park), as a result. In general, every feedback model should include a cluster of elements that will be our alternatives.

Decision-Making (Saaty, 2001) is a process that leads one to:

➢ Structure a problem as a hierarchy or a network with dependence loops.
➢ Draw judgments that reflect ideas, feelings, and emotions.
➢ Represent those judgments with meaningful numbers.
➢ Synthesize results.

In making a decision, we need to make a distinction between the hierarchic and the network structures.

In a hierarchy we have levels arranged in a descending order of importance, while in a network the components (the counterparts of levels in a hierarchy) are not arranged in any particular order, but are connected as appropriate in pairs with direct lines.

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The elements in each level of a hierarchy are compared according to dominance or influence with respect to the elements in the level immediately above that level, while in a network the pairwise comparisons of elements in a component are made according to the dominance of influence of each member of a pair on an element in the same or in another component. Additionally, in a network, the system of components may be regarded as elements that interact and influence each other with respect to a criterion or property (called a control criterion), which has to be of a higher order of complexity (or magnitude) than the elements contained in the components. The result is that such a control criterion serves as the basis for all comparisons made for both the components and for their elements.

In a hierarchy, the arrows descend downwards from the goal, to simulate the action of influence on higher levels. A remark for this would be that the arrows descend downwards even though influence is sought for in elements in the lower levels that contribute to the well-being and success of elements in higher levels. In a network an arrow points from one component to another to simulate the influence of the elements of the second component on those in the first component, or it can be a double arrow which means that elements feed back and forth into each the other, forming cycles.

In a hierarchy one does not compare levels according to influence because they are already arranged in a predetermined order of importance from top to bottom, the criteria for comparisons being included in a level, or more often implicitly replaced by using the idea of “importance, preference or likelihood” with respect to the goal, without being more finely detailed about what kind of importance it is. The control criteria for
comparisons in a network are intended to be explicit about the importance of influence, which they represent.

Regarding the questions one has to put for making comparisons, in a hierarchy we ask: "which of two elements is more dominant or has more influence (or is influenced more) with respect to a certain element in the level above?", while in a network we ask: "which of two elements is more dominant in influencing another element with respect to the control criterion?".

ANP not only has a better structure deriving from a strict understanding of the flow of influence, but in the same time allows the structure to develop more naturally, being a better way to describe what can happen in the real world. In the ANP case we are excused from ordering the components in the form of a direct chain as in a hierarchy, so we can structure any decision-making we may have to do as a direct network.

By following all of the above observations one can easily conclude that hierarchic decisions, because of the imposed structure are likely to be more subjective and predetermined. Further, by including dependence and feedback and by cycling their influence using the supermatrix, we can conclude that ANP is more objective and more likely to capture what happens in the real world, doing things that the mind cannot do in a precise and thorough way.

Putting all of these observations together, the ANP should be a better decision-making tool than the AHP.

Taking also in account that for simpler decisions AHP would be a better decision-making tool than ANP, which requires more work to capture the facts and interactions and is used
in solving complex problems where we have no other alternative, the ANP becomes just moderately better than AHP.

So we can conclude that ANP will become a standard way to make major decisions, while AHP will be the standard way for making simple and moderate decisions. Both AHP and ANP had to wait the computer age to find their use, but while in the AHP case the computer use can be avoided in simple cases, definitely when we want to capture the overall influence with ANP using the supermatrix, computer use is imperative. (adapted from Saaty, 2001, pp.179-182).

Since the question I put at the beginning of the Chapter 2 “what is the link between GIS and Decision-Making?” wasn’t a rhetorical one, in the next paragraphs, I’ll try to find some answers, with respect to the case study.

**The Case Study Picture**

Decision Making and GIS are very much related to one another. Here, we will proceed to discuss their relationship and various facts that link them, with regard of the both methods used in the case study.

As stated in the title, the objective of this thesis was to discover the role GIS is playing in decision-making and vice versa (kind of a feedback, isn’t it?), by comparing two different methods, with different approaches. Because of the practical nature of the problem, the “first decision” made was to use a GIS as a decision-making tool for the case study. Because of the data, which was readily available for use, the Lake Nakuru National Park case study was chosen and after a thorough work, completed.
All we have to do now is to reflect upon the case study to notice if indeed using the GIS was an effective option, on first hand, and on the second to see what problems regarding GIS, if any, arose during the case study.

The first major decision that had to be made in Part I of the case study was regarding the factors and constraints. There were the same four factors and one constraint for both cases of part I. In this case the GIS wasn’t playing any role, mainly because we had to rank and establish weights for the factors.

The point where GIS really started to count was in the creation of the four factors and constraint maps, followed by the creation of the two suitability maps in the multi-criteria evaluation (MCE) process. It was not only that GIS was starting to count at this point, but it was extremely useful in this process as it processed and analyzed data to give us the two suitability maps, one for industrial land use (INDSUIT) and the other for residential land use (RESSUIT).

This was the turning point where the analysis needed to be extended to another hierarchical level, by considering the two suitability maps resulted from separate multi-criteria evaluation (MCE), as if they were factors to the next level of analysis. Since we did see these two objectives as complementary, not competing for the same land and resources, we needed to solve this multi-objective problem, using an extension of multi-criteria evaluation (MCE).

This was the case were GIS via IDRISI played the most important role by far by being a decision-maker and not a decision-making tool as it was until this point, since the only point were the human decision, via the actual researcher, intervened, was in establishing the weights 0.6 and 0.4 for industrial and residential, suggesting that the
areas judged to be suitable for urbanization will be those slightly favoring industrial needs. RANK and RECLASS were the last procedures, used by the decision-maker (GIS via IDRISI) in order to get the final result that combined the two complementary objectives, industrial and residential, into a single allocation for urban uses.

As mentioned in Chapter 2, Hazelton (1996) said that decision-making is a choice between alternatives. In the Nakuru case study, we had to choose again and again between alternatives, choices of which some had been human ones. Yet GIS made the final decision, based on analyzing factors and constraints. Based on this we can say that the GIS were part of the team, acting not only like a decision-making tool, but also like a decision-maker.

For Part II of the case study the decision-making process was a little bit more complex, because of the choices regarding alternatives, clusters, the elements in the clusters, how to relate them (dependencies), in other words, the creation of the feedback network, which was entirely human-based. After the creation of the network, the participatory decision-making group started eliciting judgments, by comparing clusters and elements, first through the questionnaire option of the Super-Decisions for ANP software, and afterwards by putting them in pairwise comparison matrices for getting the priority vectors. Still, at this stage, the balance was still inclined on the human-based decision side. From this point on until the end, GIS via Super-Decisions was the only decision-maker, by calculating the supermatrices, weighing, limiting the priorities and coming up with the overall synthesized priorities for the “alternatives”.

We can say that for the Part II of the case study the result GIS decision-making vs. GIS decision-maker was a draw.
CHAPTER 7

CONCLUSION AND FURTHER SUGGESTIONS

While in the first part of the case study we had a land allocation problem, in which the final product was a suitability map, hence a quantitative product, in the second part we analyzed the long-term economic impact of the land allocation, the final product being was a synthesis of alternatives, showing the economic impact, hence qualitative.

The IDRISI software used in the first part of the case study contains and utilizes AHP’s characteristics by employing modules like: Weight, Multi-Criteria Evaluation (MCE), Rank, and Reclass. The SuperDecisions software used in the second part used the entire methodology of ANP for coming-out with the overall priorities of the Long Term Economical Benefits for the Nakuru area.

Definitely, GIS is a multi-purpose tool. Taking another view over the case study, we can see that it stored and organized data for easy retrieval, it created maps, allowing us to identify relationships between map features, and also it used the digital data for automated analysis. All these functions are very useful tools for the GIS analyst in the decision-making process.
In the first part of Lake Nakuru case study, the most important function of GIS regarding the decision-making process was probably the ability to associate information with a feature on a map in order to create new relationships that eventually determined suitable locations for the urban use. In the second part it was the ability to create the feedback network model, to perform complex analysis and to come out with the overall synthesized priorities, which represent the long-term economic benefits for the Nakuru area.

I found that using GIS via IDRISI and SuperDecisions programs was an interesting, challenging and rewarding trip that ultimately came with some original and useful results.

The whole process wasn’t at all smooth, a lot of problems being encountered during the entire trip. First it was the process of creating all of the intermediate maps, to get the suitability maps and again combining the industrial and residential before we could get the final one – the urban use suitability map.

I would like to suggest further development of IDRISI in such a way, that after feeding in the information, the analyst can get the final map without having to create the entire intermediate ones.

While the ANP’s software, Super-Decisions is more a decision-making one, it was used to analyze the Long Term Economic Benefits for the Nakuru area, continuing the work that had been done in the first part of the case study, from the decision-making point of view.

The software is interesting, but complex in the same time, and by its structure the intermediate steps have been avoided. After the network was created and weights
assigned, otherwise a long and tiresome process in which over one hundred twenty pairwise comparisons were made, the overall priorities had been obtained without going to every step, like in IDRISI.

While the AHP via IDRISI is dealing more with the quantity because of the maps, the ANP via Super-Decisions is more dedicated to the quality because of the final priorities, regarding both GIS and Decision-Making.

As GIS technology is continuously developed, I consider it very fortunate for the GIS industry to have the ANP methodology implemented, and by saying this, I acknowledge that one of the major problems GIS is having, and that it is its inability to do predictive modeling, could be solved by implementing the ANP methodology into the GIS. Therefore further research needs to be done in this direction, especially for the creation of a GIS software that will exclusively work based on ANP method.

Even though it was found that participatory decision-making would be ideal, it was impossible for the actual researcher to be in the field to consult with the people from Nakuru area, having no other choice but to make his own decisions and pass these to AHP's and ANP's software.
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Stevens D. and Thompson D., 1996, GIS as a Social Practice: Considerations for a Developing Country, *Paper presented at GIS/LIS Conference* (pp. 1-10)
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<th>Cluster 4</th>
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<td>1 TOURISM</td>
<td>2 ENVIR</td>
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**Sum** 5 4.99999 4 4 5 5 5 4 4.00001 2 1.99999

**WHERE:**
1 INDUSTRIAL 1 TOURISM 1 EXISTING ROADS 1 CONSTRUCTION COSTS
2 RESIDENTIAL 2 ENVIRONMENTAL 2 TRANSPORTATION 3 FLOOR AREAS

Table 5.1: The Unweighted Suprematrix
<table>
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<tr>
<th></th>
<th>1 ALTERNATIVES</th>
<th>2 DISTANCE FROM PARK</th>
<th>3 PROXIMITY TO ROADS</th>
<th>4 PROXIMITY TO TOWN</th>
<th>5 SLOPE GRADIENT</th>
</tr>
</thead>
<tbody>
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<td>0.058138</td>
<td>0.073677</td>
<td>0.158389</td>
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<td>2 DISTANCE FROM PARK</td>
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<td>0.060539</td>
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<td><strong>1.000000</strong></td>
<td><strong>1.000000</strong></td>
<td><strong>1.000000</strong></td>
<td><strong>1.000000</strong></td>
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Table 5.2: Component (Cluster) Influence Matrix
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<th>Cluster 4</th>
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WHERE:
1 INDUSTRIAL  1 TOURISM  1 EXISTING ROADS  1 CONSTRUCTION COSTS
2 RESIDENTIAL 2 ENVIRONMENTAL 2 TRANSPORTATION 2 SERVICES  2 EROSION
3 FLOOR AREAS 3 FLOOR AREAS

Table 5.3: The Weighted Supermatrix
<table>
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**Sum**: 1.0000 1.0000 1.0000 1.0000 1.0000

**WHERE**:
- 1 INDUSTRIAL
- 2 RESIDENTIAL
- 1 TOURISM
- 2 ENVIRONMENTAL
- 1 EXISTING ROADS
- 2 TRANSPORTATION
- 2 SERVICES
- 1 CONSTRUCTION COSTS
- 2 EROSION
- 3 FLOOR AREAS

Table 5.4: The Limit Supermatrix
Priorities from Limit Supermatrix | Priorities Normalized by Cluster
---|---
1 Alternatives | 0.06455 | 0.43792
2 | 0.04874 | 0.33066
3 Park | 0.03411 | 0.23141
Sum | 0.14740 | 1
2 Distance from Park | 0.04562 | 0.58004
1 Tourism | 0.03303 | 0.41996
2 Environmental Pollution | 0.07865 | 1
Sum | 0.07865 | 1
3 Proximity to Roads | 0.16276 | 0.44464
1 Existing Roads | 0.20329 | 0.55536
2 Transportation | 0.36605 | 1
Sum | 0.36605 | 1
4 Proximity to Town | 0.12197 | 0.49634
1 Labor | 0.12377 | 0.50366
2 Services | 0.24574 | 1
Sum | 0.24574 | 1
5 Slope Gradient | 0.08960 | 0.55247
1 Construction Costs | 0.04654 | 0.28697
2 Erosion | 0.02604 | 0.16056
3 Floor Areas | 0.16218 | 1
Sum | 0.16218 | 1

Table 5.5: Overall Priorities Obtained from Limit Supermatrix
### Pairwise Comparison of C1 Alternatives with NHI Labor

<table>
<thead>
<tr>
<th>Factor</th>
<th>C1 Alternative 1</th>
<th>C1 Alternative 2</th>
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</thead>
<tbody>
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### Pairwise Comparison of C1 Alternatives with NHI Services

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<tbody>
<tr>
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### Pairwise Comparison of C1 Alternatives with NHI Construction Costs

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<tbody>
<tr>
<td></td>
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### Pairwise Comparison of C1 Alternatives with NHI Erosion

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<th>Score</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</table>

### Pairwise Comparison of C1 Alternatives with NHI Floor Areas

<table>
<thead>
<tr>
<th>Factor</th>
<th>C1 Alternative 1</th>
<th>C1 Alternative 2</th>
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<th>Score</th>
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</thead>
<tbody>
<tr>
<td></td>
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### Pairwise Comparison of C2 Distance From Park with NHI Industrial

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<tbody>
<tr>
<td></td>
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120
Pairwise Comparisons of C2 Distance from Park vs N4Z Residential

Pairwise Comparisons of C2 Distance from Park vs N4Z Transportation

Pairwise Comparisons of C4 Distance from Park vs N4Z Existing Roads

Pairwise Comparisons of C4 Distance from Park vs N4Z Labor

Pairwise Comparisons of C4 Distance from Park vs N4Z Services

121
The Eigen Vector and the Matrix of Pairwise Comparisons for the C1 Alternatives w.r.t N12 Residential

The Eigen Vector and the Matrix of Pairwise Comparisons for the C1 Alternatives w.r.t N13 Park

The Eigen Vector and the Matrix of Pairwise Comparisons for the C1 Alternatives w.r.t N21 Tourism

The Eigen Vector and the Matrix of Pairwise Comparisons for the C1 Alternatives w.r.t N22 Environmental Pollution

The Eigen Vector and the Matrix of Pairwise Comparisons for the C1 Alternatives w.r.t N31 Existing Roads

The Eigen Vector and the Matrix of Pairwise Comparisons for the C1 Alternatives w.r.t N32 Transportation