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Kershaw, Claude Ian.

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SPATIAL DECISION SUPPORT SYSTEM FOR THE SELECTION OF AN OVERHEAD ELECTRICAL TRANSMISSION LINE CORRIDOR

Claude Ian Kershaw

A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, in fulfilment of the requirements of the degree of Master of Science in Engineering.

Johannesburg, 2011

Declaration

This dissertation is being submitted for the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg.

I declare that this dissertation is my own unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other university.

_____

C.I. Kershaw

10th Day of February 2011

Abstract

This dissertation presents research into the possibility of using GIS Spatial Analysis and Multi-Criteria Decision Making to determine a corridor for electric overhead transmission power line routing.

The research described in this dissertation examines the feasibility of developing a spatial decision support system to select an overhead transmission line corridor. This support system could also be used to perform scenario analysis.

The selection model evaluates multiple environmental, ecological, electrical, aesthetic, engineering and socio-economic criteria spatially. Each criterion is weighted using a pair-wise comparison and is presented as a GIS layer. A suitability map is derived from the weighted layers using a weighted linear combination.

A least cost path that represents the corridor most likely to contain the optimum route for an overhead electrical transmission line is derived from the suitability map.

Dedication

To my wife Priscilla and son Claude for their love and support

Acknowledgements

Professor Barry Dwolatzky, for his guidance, supervision and encouragement.

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All those who have contributed in any way, shape or form to the completion of this research. Those at Eskom for their advice and support, friends for their ideas and criticisms.

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Abbreviations

AHP	Analytic Hierarchy Process
DBMS	Data Base Management System
DSS	Decision Support System
ESIGIS	Eskom's Corporate GIS Department
GIS	Geographical Information System
GPS	Global Positioning System
MADM	Multi Attribute Decision Making
MCDM	Multi Criteria Decision Making
MCSDM	Multi Criteria Spatial Decision Making
OETL	Overhead Electrical Transmission Line
SAW	Simple Additive Weighting
SDSS	Spatial Decision Support System
SMCDM	Spatial Multi-Criteria Decision Making
SME	Subject Matter Expert
WLC	Weighted Linear Combination

1 Introduction

1.1 Background

To meet the increased demand for electrical power in South Africa a number of new Overhead Electrical Transmission Lines (OETL) will be planned within the next 5 years. Routes for these new OETL's will be selected by determining a corridor within which a final route can be negotiated with the landowners.

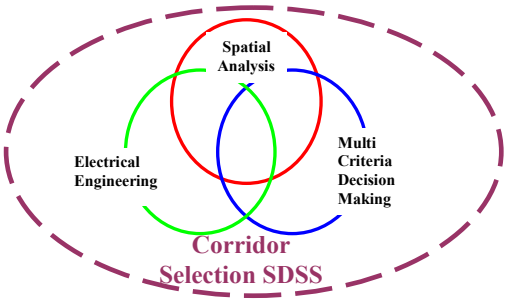
The process of selecting a suitable corridor for an OETL is always complex. It covers a large area and involves a wide range of stakeholder groups. These stakeholders often have competing objectives [1]. To find a solution to these complex issues requires a socio-technical perspective [2].

This project researched the possibility of developing a model that utilises GIS and Multi-Criteria Decision Making (MCDM) to determine a suitable corridor for electrical overhead transmission lines and secondly investigated ways to present the decisions to interested parties.

This research was conducted in response to a need identified by Eskom's Corporate GIS Department (ESIGIS). The need as identified by ESIGIS was for a model making use of spatial data and spatial analysis to facilitate the corridor selection process. Eskom is currently planning a number of new routes and such a model would assist in reducing the time to select suitable alternative routes by allowing multiple alternatives to be considered in less time than traditional methods.

The Corridor Selection Spatial Decision Support System presented combines Electrical Engineering, Spatial Analysis and Multi-Criteria Decision Making in selecting a corridor. The system considers multiple criteria to determine areas that should be avoided and points to include in a corridor. The corridor selected is an indication of the area most likely to contain a suitable route.

Such a model would be helpful as a planning tool to evaluate possible corridor selection alternatives. The ability to model the route selection process of a power line could allow environmentally sensitive areas to be avoided and thus protected.



Overview

1.2 Introduction

Decision Support Systems (DSS) and, more recently, Spatial Decision Support Systems (SDSS) are increasingly popular tools in the decision-making process. The reasons for the popularity of such tools can partly be found in the development of the technology, which makes it possible to install and use the systems on personal computers, and partly in the need to manage the large amounts of often-complicated data that forms part of the decision-making processes [3]. There are numerous definitions for DSS but in this research that of (Janssen, 1992) in [4] is used:

A DSS implies a computer program that:

- Assists individuals or groups of individuals in their decision process;
- Supports rather than replaces judgments of individuals;
- Improves the effectiveness rather than the efficiency of a decision process.

A SDSS is different from a DSS in that it is used to support the decision-making processes where the spatial nature of the problem plays a decisive role in making the decision. Despite ongoing discussions, there is no agreement on a single definition for SDSS's. (Fotheringham, 1990) in [4] compares this discussion to "*defining a car: there seems to be general agreement on what it is, but not on what are the necessary attributes for giving it such a label*". This explains why

most authors simply end up with a list of characteristics of what a SDSS might be comprised of.

This research investigated the possibility of using a Spatial Decision Support System to select corridors for Overhead Electrical Transmission Lines. The Summary of the Literature presented in chapter 2 reviews the principles that could be used to perform spatial multi-criteria corridor selection. Chapter 3 outlines the methodology followed in conducting this research. Chapter 4 describes the methodology of selecting a corridor for an OETL taking multiple spatial criteria into account. In chapter 5, the effectiveness of the process is evaluated by using the model to select a corridor for three different scenarios. Chapters 6 and 7 discuss the results and conclusions respectively.

2 Review of the Literature

2.1 Corridor Selection for Overhead Electrical Transmission Line

Corridor selection is an activity that has been done for many years. Over time, the methods used have changed but the underlying principles remain the same in so far as information about the environment and stakeholders preferences is used to make decisions on where to route an overhead electrical transmission line (OETL).

Modern technologies have resulted in the need to process vast amounts of data and at the same time consider the requirements of stakeholders who may have different priorities.

OETL corridor selection problems share many characteristics of other public infrastructure location questions, including landfills, roads and waste disposal sites [2]. The process of selecting the most suitable corridor is always complex. It covers a large area and involves a wide range of stakeholder groups with often competing objectives [5].

Locating a corridor connecting an origin and a destination substation is similar to identifying a route that traverses a continuous landscape [5]. Corridor analysis for most linear features such as a OETL or a road is therefore similar to finding the shortest-path using network analysis in raster GIS and continues to evolve along with it [5]. Corridor analysis can also be considered a variant of surface analysis in that it can be viewed as a site selection problem where an optimal contiguous and elongated site is required [5].

The evaluation of the impact that an OETL will have on the environmental requires the coordination of factors such as ecological, electrical, aesthetic and socio-economic factors. In order to minimize the impact on the environment caused by OETL's they should be designed considering the following [6]:

2.1.1 Ecological Factors

- Vegetation
- Wildlife habitats
- Pristine or unique habitats
- Rare and/or endangered species
- Bird nesting areas

2.1.2 Electrical Factors

- Existing linear infrastructure
- Existing land use (Agriculture mining residential etc)
- Audible noise
- Meteorological data

2.1.3 Aesthetic Factors

- Visual
- Hydrology
- Soils

2.1.4 Social Factors

- Existing / proposed land use
- Population estimates
- Industrial growth estimates
- Economic data
- Present lifestyle

GIS is increasingly being used by professionals to manage, monitor and visualize these and other factors related to an electrical power system. The objectives of all professionals participating in the process of selecting a corridor for an OETL should be compatible with the following ecological, aesthetic and socio-economic principles [6] :

- Minimize damage to natural systems

- Minimize conflict with existing land use
- Minimize conflict with proposed land use
- Minimize impact on culturally significant features
- Minimize visual impact
- Maximize potential for right of way sharing

Irrespective of the manner in which a corridor for an OETL is selected, for it to be accepted by the widest possible audience the corridor selection methodology should be based on the following principles [6]:

- Respect for all stakeholders by considering their input and making effective use of this information to influence corridor determination.
- The selection process must be seen to be fair.
- Transparent. Offer each stakeholder group the opportunity to see and understand the priority system of other stakeholder groups.
- Efficient. Generate useful, easily understood options.

2.2 Spatial Informatics and GIS in Electrical Power Systems

Urban growth coupled with the densification of existing urban areas has resulted in increased demand for electrical energy. This growth has also meant that there is less land available for locating the infrastructure that makes up an electrical power system. The cost of acquiring and maintaining the land and the need to reduce technical losses results in the need for efficient planning of extensions to the power system. GIS can be used as an aid in designing power system networks.

Making use of GIS to plan and design the power system network can maximize the efficiency of the power system and reduce the impact that the erection of OETL's may have on the environment. Apart from its ability to perform analysis based on the location of objects GIS is useful in the planning process as the Database Management System (DBMS) that is part of the GIS allows [7]:

- Data from outside sources to be incorporated
- Data to be easily updated
- The database to be queried

The GIS allows the planning engineer to combine the land base, demographic data and electrical network maps with any other spatial and non-spatial data. The planning engineer can then analyze these combined maps using spatial analysis and conventional data mining techniques to optimize decisions. The GIS is also used to generate reports and visualize the results derived during the analysis. During the analysis location data is linked with attribute data, it is this link, which is automatically performed by the GIS software that gives GIS its analytical power [8]. GIS also eliminates the need to use traditional survey techniques to locate infrastructure due to its interface with GPS [7].

GIS has the ability to reveal aspects of a decision that would otherwise be difficult to detect. This useful characteristic of GIS is helpful in corridor selection, giving more insight into the problem. The problems associated with corridor selection are always complex, not easy to solve unless we integrate spatial concepts with traditional, conventional and available routing solutions [7].

When selecting a corridor for an OETL, a straight corridor with minimum bends is desirable as it gives the best engineering and economic solution [7]. This ideal corridor may have to pass through places, which are already inhabited by people, environmentally sensitive areas or areas that are not suitable for locating OETL towers. Depending on the costs involved, a decision to find an alternative corridor, move the inhabitants or find an environmentally acceptable solution has to be made. GIS is increasingly being used to assist in making these types of decisions. GIS and multi criteria decision making techniques can be used to determine suitable areas for locating OETL's taking into account many factors such as the impact on the environment or engineering considerations. GIS can implement optimal routing algorithms based on electrical and material properties in addition to the location requirements and allow the network to be visualized on a map, making it an ideal tool with which to perform scenario analysis [7].

2.3 Geographical Information Systems

"GIS should be viewed as *a process rather than as merely software or hardware."* [3]

GIS and Spatial analysis can be applied in many different ways and is useful in making decisions such as where to route an OETL. With GIS it is possible to perform functions that facilitate data input, data storage and management, data manipulation and analysis, and data output for both spatial and attribute data [3]. GIS and Spatial Analysis is used to convert the raw data to information that is useful in the decision making process.

2.3.1 Data Input

"*The data input component* converts *data from their raw or existing form into one that can be used by a GIS*" [3]. This involves the acquisition, reformatting, geo-referencing, compiling, and documentation of the data. The following are some of the methods used to acquire spatial data:

- Digitizing
- Scanning
- Remote sensing
- Global positioning systems

2.3.2 Data Output

"The data output component of GIS provides a way to see the data, information and results in the form of maps, tables, diagrams. The results may be generated in hard-copy, soft-copy, or electronic format (Aronoff 1989; Pazner et al. 1993; DeMers 1997)" in [3].

Data output can be classified into the following four categories: [3]

- Text outputs are tables, lists, numbers or text in response to queries.
- Graphic outputs are maps, screen displays, diagrams, graphs.

- Digital data is data stored on disk or tape, or transmitted across a network.
- Other forms of output are computer generated sound and video clips.

2.3.3 Data Storage and Management

"GIS-based decision analysis requires representation of real-world geographical systems in digital format. The *real-world geographical systems are too complex for even the most advanced information systems, and they must therefore be simplified" [3].* This simplification of reality is referred to as a data model and is implemented in a database.

Data storage and management functions are those functions that are needed to store and retrieve data from the database. The attributes (tabular data) of the entity are stored in a database and attached to the spatial object by an identifier also referred to as a key.

Geographical objects are described by two types of data [3]:

- Location data
  Relates the object to its position in geographical space
- Attribute data
  Describes other properties of the object apart from its position

In GIS a database management system (DBMS) is used for handling these two types of data. Most standard databases are classified according to a model of how the data are viewed by the user. "*A great number of data models have been proposed, such as flat data structure, hierarchical, network, relational, and object-oriented models (Aronoff 1989; Huxhold 1991; De Mers 1997)"* in [3]. Two of the most popular data models are relational and flat data models and both are used extensively for GIS-based multi-criteria decision analysis. The relational model is the most popular database used to organize data in GIS while the flat data model is a convenient way to store and process data for multi-criteria decision making (Kirkwood 1997) in [3].

2.3.4 Raster vs. Vector Data

Spatial data which is at the heart of the corridor selection process can be saved in either raster or vector format. Each format has advantages and disadvantages over one another.

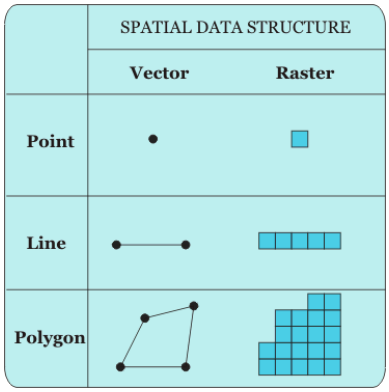


Figure 2.1 - Spatial Data Structure [3]

According to Shree et al. [9] in vector GIS, spatial data are defined and represented as ‘points’, ‘lines’ or ‘polygons’. A point is defined by a single set of coordinates. Examples of point data for corridor selection applications may include features such as graves, wind pumps and small buildings. In vector GIS, lines can be used to represent features such as roads, rivers and railway lines. Lines have starting and ending points, which are referred to as ‘nodes’. A line may include a large number of ‘vertices’ (bends in the line). The segment of a line between two vertices is referred to as an ‘arc’. Polygons are used in vector GIS to represent enclosed areas. A polygon consists of a number of lines. The difference between a polygon and a line is that a polygon’s starting and ending nodes are the same. In corridor selection using vector GIS dams, wetlands and land classification can be represented as polygons. A vector GIS knows where the spatial feature (point, line or polygon) is located as well as its relationship to other features (topology or relative location). A GIS would therefore be aware that a dam supplying water to a town is located to the north of the town.

After spatial features are represented in vector GIS the associated attributes are specified in a database. As an example, properties of a land use polygon such as the number of households, household density, population density or income level

can be saved in a database. These attributes are often referred to as ‘themes’, which can be presented in so called ‘thematic maps’. Vector GIS lend themselves well to the use of relational databases because after the spatial features are specified (once), any amount of related data can be associated with them [9]. The term feature class is used in the GIS literature to refer to the combination of geographically referenced features and its associated data. Thus, a ‘river feature class’ would refer to the line in a vector GIS that represents its course, and the associated data such as flow rates and water temperature.

In raster GIS systems [9], geo-referenced data stored in a grid constitute a ‘layer’, as opposed to a feature class in vector GIS systems. Each grid contains a unique set of information. Thus, each of the land use attributes described above for vector GIS would be stored in a separate layer if a raster system is used. In other words, there would be as many layers as there are properties of the spatial feature. Consequently, data storage requirements for raster GIS are generally higher than comparable vector systems. Further, if there is a need to integrate different layers that describe a certain feature, the process may also be more costly in terms of access time. These disadvantages are perhaps less important in present day computers because large hard disks are not only relatively inexpensive, but also allow rapid data retrieval. A more important disadvantage of raster GIS is that the spatial resolution of analyses is limited to the cell size of the coarsest layer. When the cell size is large relative to the scale of analysis maps created from raster data tend to be somewhat blotchy.

In spite of other shortcomings, because of the uniform grid structure raster systems are particularly useful when it comes to numerical manipulations. For instance, they lend themselves well to spatial modelling applications [9]. As an example, a water temperature simulation model can be executed with weather datasets (e.g. air temperature, solar radiation, cloud cover, relative humidity, and wind speed) in the form of raster inputs. Output from the model can be exported to a gridded file, which in turn can be imported into raster systems for further classification and display (Kapetsky and Nath, 1997) in [9]. Similarly, raster GIS can be used to model the slope of an area by applying appropriate equations to

cells in the spatial grid. Another advantage of raster GIS is that remote sensed data (which are usually stored in raster format) can often be directly imported into the software and immediately become available for use (Burrough, P.A., 1986. Principles of Geographic Information Systems (1st ed.), Oxford University Press, New York, 336 pp. Burrough, 1986) in [9].

One of the powerful features of both vector and raster GIS packages are that statistical summaries of feature classes/layers, model stages or outcomes can easily be obtained. Statistical data can include area, perimeter and other quantitative estimates, including reports of variance and comparison among images. A further powerful analytical tool that aids the understanding of outcomes is the visualization of the outcomes through graphical representation in the form of 2D and 3D maps. For example, entire landscapes and watersheds can be viewed in three dimensions, which can be very valuable in terms of evaluating the spatial impact of alternative decisions. Techniques have also been developed to integrate GIS with additional tools such as group support systems that allow interactive scenario development and evaluation, and support communication among stakeholders via a local area network (Faber et al., 1997) in [9]. There is also currently rapid development and deployment of Internet-enabled GIS tools, which allow a wider community of decision makers to have instant access to spatial data. All of these tools are constantly being added to GIS packages and are of great value if appropriately used.

GIS requires spatial data on which to operate. The functions in a GIS convert the raw data to information. The information is in turn used to make decisions.

2.4 Geographical Data

"Geographical or spatial data is undigested, unorganized, unevaluated material that can be associated with *a location on the earth's surface. Spatial decision problems are decisions that involve geographical data and information*" [3].

"It is estimated that 80% of data used by managers and decision makers is related geographically (Worrel 1991)" in [3]. The terms spatial data and geographical

data are used interchangeably. Geographical data includes facts, results of observations, original remote sensing images and basic census figures and statistics.

2.4.1 Geographical Matrices

All decisions made in the corridor selection process rely on data. It is important to be able to arrange and organize the data in such a manner that it can be understood and interrupted during the decision making process. Geographical data used for decision-making can be arranged in two distinctive tabular forms namely [3]:

- a spatial structure data matrix
- a spatial interaction data matrix.

Table 2.1 - Structural Data Matrix [3]

	Attribute 1	Attribute 2	…	Attribute $_n$
Entity 1	x_{11}	x_{12}	…	x_{1n}
Entity 2	x_{21}	x_{22}	…	x_{2n}
…	…	…	…	…
Entity $_m$	x_{m1}	x_{m2}	…	x_{mn}

Table **2.1 - Structural Data Matrix [3]**displays the structure of a structural data matrix. The geographical entities for which data are required are represented by the rows of the matrix. The rows are numbered in sequence 1, 2, 3, .., i,…, m where i stands for an individual entity and m is the total number of entities under consideration. Each entity is described by location data (coordinate) and attribute data (properties). An attribute can be defined as any property that distinguishes a geographical entity. The most essential property of the attributes is that their values vary over geographical space [3]. Each attribute j is represented by a column in the structure data matrix (j=1,2,3,…,n).

The intersection of any row and column in a geographical matrix defines a cell that is filled with the value of an attribute j at location i. Each cell of the geographical matrix contains a fact, an observation or assessment in numerical or

alphanumerical form. Parcels of land can be described by the name and address of the owner, the assessed values, etc. Attributes are usually grouped into two broad categories: socioeconomic and physical. The socioeconomic category includes social, economic, and political characteristics such as population density, income, employment, unemployment level, quality of life, social status, religion, and language. The physical category can be disaggregated into geological, geomorphologic, climatic, hydrologic, biotic classes of attributes. Each class can be further sub-divided into more detailed categories [3].

Any column of a structure data matrix represents a single spatial distribution; this distribution can be converted into a map to show the geographical distribution of the column (e.g., land use, household income, or population density) [3]. Analysis of a single spatial distribution is referred to as single-dimensional analysis. By considering two or more columns of the structure data matrix spatial relations can be studied. The data in a structure data matrix can be used for spatial multi-criteria decision analysis [3]. Each row in a structure data matrix indicates the characteristics of a particular geographical object by describing it in terms of a set of attributes.

Table 2.2 - Spatial Interaction Data Matrix [3]

	Entity 1	Entity 2	…	Entity $_k$
Entity 1	x_{11}	x_{11}	…	x_{1k}
Entity 2	x_{21}	x_{22}	…	x_{2k}
…	…	…	…	…
Entity $_m$	x_{m1}	x_{m2}	…	x_{mk}

Table **2.2** shows an interaction data matrix. The rows and columns of the matrix both refer to the entities of a geographical system. They represent the geographical entities for which data are required. The rows and columns are numbered in the sequence 1, 2, 3, ..., i, … , m and 1, 2, 3, ..., j, ..., k, respectively. The number of rows and columns need not be equal, and it is not required that the entities listed in the rows correspond to the entities in the columns [3].

In a spatial interaction data matrix x_{ij} represents the relationships between the ith and jth entities. These relationships may be either measured or assessed levels of interaction between the two entities. They can also be expressed in terms of distance, time, cost of getting from i to j, or the degree of connectivity between the two entities. Thus each cell of the matrix is filled by a value representing the relationship between entities i and j.

A large number of operations that are useful in the context of spatial decision making and that are related to the following questions can be performed on the data contained in the spatial interaction data matrix [3]:

- what is the volume originating at each node (sum of a row)?
- what is the volume terminated at each destination (sum of a column)?
- what is the allocation of the flow column from origins to destinations (the individual cell totals in the matrix)?

A sequence of interaction matrices can be used to represent changes in the spatial data over time [3].

Geographical matrices are fundamental in organizing data to be used in spatial decision analysis [3]. Geographical data for site selection, land suitability, and land use can be organized in terms of a matrix, where the rows represent alternative decisions (e.g., sites or parcels of land) and the columns contain the evaluation criteria. The spatial interaction matrix provides a base for organizing data for the location-allocation problem, shortest-path problem and routing problem [3]. "*Many decision situations require data on both attributes and spatial relationships. A combination of the two tabular representations can be used to organize the input data for spatial decision making"* [3].

2.4.2 Levels of Measurement

"In order to make decisions with geographical matrices, meaningful and accurate data are required." [3] Levels of measurement determine to what extent the data can be applied in the decision making process. Data can be either numeric or quantitative. In GIS measurement can be defined as a process of assigning

numbers to attributes of geographical entities according to a set of rules [3]. The numbers are assigned to the attributes of entities and not to the entities themselves. For example, one can measure such attributes as age, income and education of a population but not the population itself. "*There are four basic levels of measurement:* ***nominal***, ***ordinal***, ***interval***, *and* ***ratio*** *(Stevens 1946)"* in [3]. **Table 2.3** shows the major characteristics of the four levels of measurement.

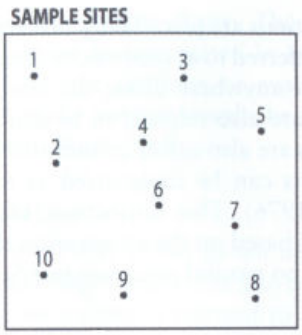
Table 2.3 - Levels of Measurement [3]

Measurement	***Characteristic***	***Valid Operations***	**Example**
Nominal	*Classification where the ordering of class values is arbitrary*	*Equal*	Urban or Rural
Ordinal	*Relative ordering made with unknown or unequal intervals between classes*	*Less than, greater than*	Primary or Secondary Road
Interval	*Continuous measurement using equal intervals made from an arbitrary zero point*	*Addition, subtraction, scaling by a constant*	Temperature in Celsius
Ratio	*Continuous measurement using equal intervals made relative to an absolute value of zero*	*Multiplication, division*	Mass in kg or Money in Rand

2.4.3 Data and information

"For data to be useful, it must be transformed into information. Geographical information is data that are geo-referenced, organized, analyzed, interpreted and considered useful for the spatial decision problem" [3].

The distinction between the concept of geographical data and geographical information can be demonstrated by means of the following example [3]: The classification of soils in a study area can be classified by their sand, clay, and silt content. The percentage sand, clay, and silt content of 10 randomly selected soil samples are determined.



MEASUREMENT (%)

Sample	Sand	Clay	Silt
1	10	85	5
2	8	86	6
3	40	52	8
4	52	43	5
5	62	30	8
6	49	45	6
7	60	31	9
8	39	20	41
9	57	31	12
10	48	49	3

Figure 2.2 - Unclassified data [3]

The values obtained from the sampling procedure have little meaning except that they indicate measurements (data), that is, the proportion of sand, clay and silt (Figure 2.2) in corresponding sample points. To derive information from the measurements we have to impose some level of organization on the raw data. One way of organizing the data is to classify the samples according to the sand, clay, and silt content. From an analysis of the sample data set, four soil classes emerge: (1) clay soils; (2) sandy clay soils; (3) sandy loams; and (4) loams. By constructing iso-lines (organizing the raw data measurements) a map representing the four soil classes can be constructed (Figure 2.3) providing us with information on the spatial pattern of the soil types.

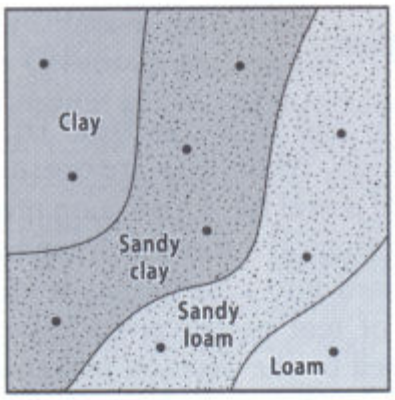


Figure 2.3 - Data Classification [3]

2.5 Fuzzy logic techniques

In a complex spatial decision support system for overhead power line routing, it is difficult (or even impossible) to provide the precise numerical information required by the conventional methods that are based on Boolean algebra [10]. For example, for some activity, there may be natural dividing boundaries between suitable and unsuitable areas (e.g. legal requirements). However, in many situations attributes associated with land use lack natural cut-offs (constraints or thresholds). In conventional approaches a cut-off is defined for example as: ”an acceptable site must not be located within 1 km of a river”. Such a cut-off is not a natural one. Why would a site 1.1 km away be acceptable and a site located within 0.99 km from a river be categorized as an unacceptable one? There is usually an ambiguity and imprecision involved in defining such constraints. In addition, the conventional methods often assume that the criterion weights are given in a numerical form. Contrary to these assumptions, the weights of importance are often specified by means of some linguistic statements that provide an ordering of the criteria for land suitability from the most important to the least important one. Therefore, issues related to vagueness, imprecision and ambiguity should find a proper place in the overhead power line routing procedures. They can be addressed by fuzzy set theory and fuzzy logic (Zadeh, 1965 and Fisher, 2000) in [10].

Fuzzy logic represents an extension of the classic binary logic, with the possibility of defining sets without clear boundaries or partial memberships of elements belonging to a given set (Zadeh, 1965) in [10]. Essentially, a fuzzy set is a set whose members have degrees of membership between 0 and 1, as opposed to a classical set where each element must have either 0 or 1 as the degree of membership. The central concept of fuzzy set theory is the membership function, which numerically represents the degree to which a given element belongs to the set. It provides a framework for representing and treating uncertainty in the sense of vagueness, imprecision, lack of information, and partial truth [10]. There are three approaches for defining fuzzy membership: the semantic import model, the similarity relation model and an experimental analysis (Burrough and McDonnell,

1998 and Fisher, 2000) in [10]. In the semantic import model, some form of expert knowledge is used to assign a membership on the basis of the measurement of some property. The similarity relation approach is based on a pattern recognition algorithm, which searches the data for fuzzy membership. The membership function can also be identified empirically by an experiment involving human subjects.

The application of fuzzy logic to spatial problems in general and land suitability modelling in particular has several advantages over the conventional methods (Hall et al., 1990; Burrough and McDonnell, 1998 and Fisher, 2000) in [10]. Given the continuous variation in geographical phenomena such as soil or vegetation classes, Burrough and McDonnell (1998) in [10] suggested that the fuzzy membership approach is appropriate in defining the boundaries between different land use classes. They also demonstrated how the conventional approaches lose information and increase the chance of errors when a spatial problem involves data corrupted by inexactness. The fuzzy set methods retain all the information of the partial memberships giving due consideration to the uncertainty involved [10]. Although the fuzzy logic approach to land use suitability modelling is shown to have fewer limitations than conventional techniques, the approach is not without problems. The main difficulties associated with applying the fuzzy logic approach to land use suitability modelling are the lack of a definite method for determining the membership function [10].

"A fuzzy set is a class of elements or objects without well defined boundaries between those objects that belong to the class *and those that do not"* [3]. Fuzzy sets allow objects to belong partly to multiple sets. Fuzzy logic is useful for describing the vagueness of entities in the real world, where belonging to a set is really a matter of degree [3].

In GIS, fuzzy sets can be used to represent geographical entities with imprecisely defined boundaries as fuzzy regions [3]. A fuzzy region can be represented as a set of cells.

"The capability of fuzzy sets to express gradual transition from membership to non-membership and vice versa has broad application not only for representing geographical entities with imprecise boundaries but also for GIS-based operations and analysis, including spatial decision analysis" [3].

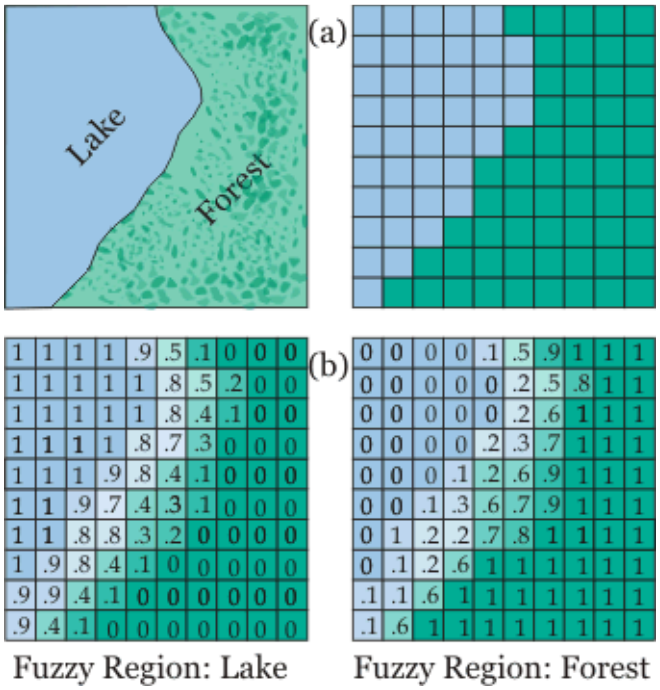


Figure 2.4 - Fuzzy Representation [3]

2.5.1 Fuzzy Set Membership

The process of standardizing evaluation criteria can also be seen as one of recasting values into a statement of set membership. It is important to define the two terms fuzzy number and linguistic variable. A fuzzy number is a fuzzy set defined on the domain of real numbers (Klir and Yuan 1995). The following special fuzzy numbers have been suggested to simplify fuzzy modelling: trapezoidal, triangular, L-R trapezoidal, and L-R triangular types as well as fuzzy numbers based on S and Z-functions (Chen and Hwang 1992; Klir and Yuan 1995; Eastman 1993, 1997). These categories of fuzzy numbers are sometimes referred to as standard membership functions. The trapezoidal category of fuzzy numbers has a relatively simple structure. It is important to note that the trapezoidal fuzzy numbers include crisp numbers, interval numbers, and

triangular numbers. An example of a trapezoidal fuzzy number is given in Figure 2.5 - Fuzzyset Membership (Bonissone 1982). The number is designated by M, where M = (a,c,α,β); that is, the number (0.1, 0.7, 0.3, 0.3) represents the trapezoid shown in the figure. Alternatively, a trapezoidal number can be written as M = (a,b,c,d). Accordingly, the trapezoid is represented by the following L-R fuzzy number: M = (0.1, 0.4, 0.7, 1.0) [3].

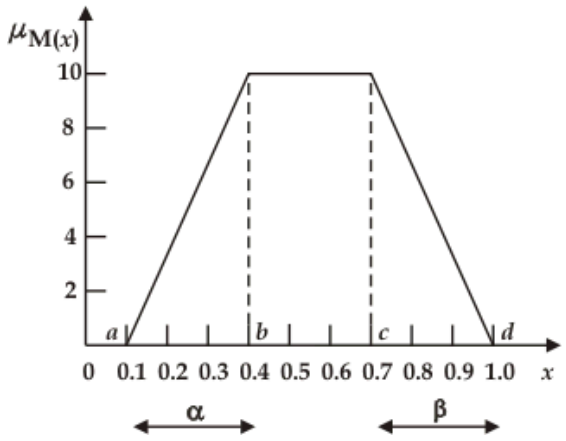


Figure 2.5 - Fuzzyset Membership [3]

The concept of a fuzzy number provides us with the basis for defining linguistic or fuzzy variables (Klir and Yuan 1995) in [3]. The fuzzy numbers are states of a linguistic variable. The states are represented by linguistic concepts such as "very short," "short," "medium," "long," "very long," "very steep," "steep," "small," "medium," "large," and so on. These concepts are defined in terms of a base variable, the values of which are real numbers within a specific range. A base variable is a variable in the conventional sense: for example, distance, slope, temperature, moisture, precipitation, and so on. The following example illustrates the concept of fuzzy numbers and linguistic variables.

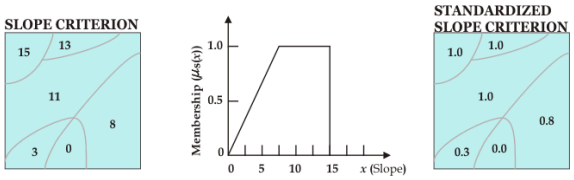


Figure 2.6 - Standardised Criterion [3]

The concept of a fuzzy number can be illustrated using a slope criterion map (Figure 2.6). The map displays the percentage slope gradients in a region. The map can be converted to standardised form using the fuzzy number representing the concept of "steep slope." Let us assume that "a slope is considered to be steep if it is greater than or equal to 10%." This statement can be represented by a triangular fuzzy number, S = (0, 1, 1, 1). Given this number, the original slope criterion map can be transformed to a fuzzy (standardised) criterion map. Each spatial unit (slope attribute value) is assigned a value ranging from 0 to 1, indicating the degree of membership in the fuzzy set.

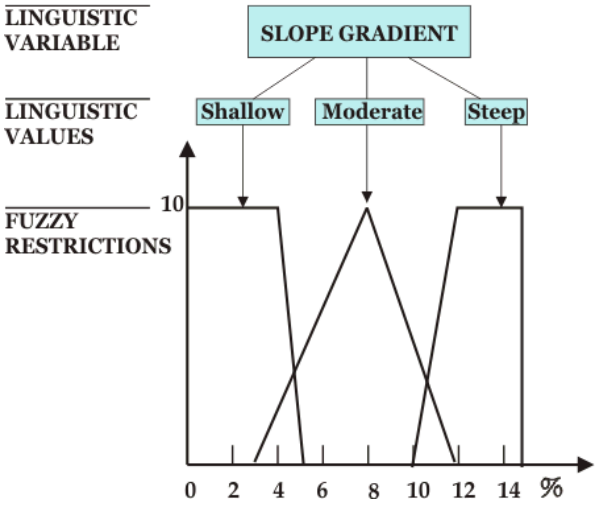


Figure 2.7 - Linguistic Variable [3]

Figure 2.7 shows an example of a linguistic variable called slope gradient. The variable represents the slope steepness (in percent) in a given context by three linguistic terms: "steep," "moderate," and "shallow." Each of these linguistic terms is assigned one of three fuzzy numbers. The numbers are represented by the trapezoidal or triangular membership functions defined on the range [0,15] of the base variable (slope). The fuzzy numbers express a fuzzy restriction on this range. The restriction is a fuzzy relation that is used as a flexible constraint on the values that may be assigned to a linguistic variable. Given the fuzzy numbers, linguistic terms can be assigned to a spatial unit to represent the different degree of "slope steepness." For example, the unit characterized by the slope value of 15% is

assigned the "steep" label; the spatial unit containing the value of 8 falls into the "moderate" category, and so on (Figure 2.7).

2.6 Map Layers

"A map layer is a set of data describing a single characteristic of each location within a bounded geographical area" [3]. Only one item of information is available for each location within a single layer. Layers can be thought of as being similar to individual overhead transparencies that can be placed on top of each other to show spatial relationships between them. Each map layer contains information of a different nature and can be thought of as a variable. A single layer may represent a single entity type or a group of conceptually related entity types. For example, a map layer may contain only highways or may represent an entire transportation network, including secondary routes, a network of streets, subway lines, and so on.

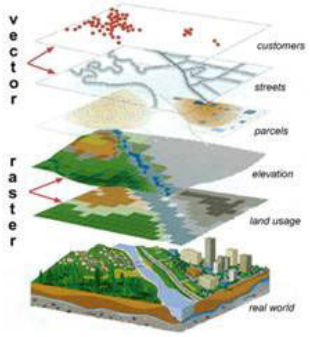


Figure 2.8 - Map Layers

2.7 Data Manipulation and Analysis

A distinguishing feature of GIS systems is their ability to perform analysis of both spatial and attribute data. The data are manipulated and analyzed to obtain information useful for a particular decision [3]. Some useful fundamental GIS functions used to create the input spatial data in MCDM are:

- Measurement
- (Re)Classification

- Scalar
- Overlay operations
- Neighbourhood
- Connectivity operations

Measurement. The measurement functions within GIS enable calculations associated with points, lines, areas, and volumes (Dangermond 1996; DeMers 1997) in [3] to be performed.

(Re)classification. "*Reclassification and classification operations transform the attribute data associated with a single map layer (Davis 1996; DeMers 1997)"* in [3]. These functions involve the grouping of input data objects into classes according to the new values assigned to these objects. These new values are derived for certain location and non-location attribute values.

Scalar operations. "*This class of operation makes use of a single, uniform value and a scalar data layer*." It is constructed by assigning a value to each location on the data layer. One primary use for scalar operations is to transform all objects of an existing data layer in order to change all values by a given value. The output data layer will then consist of new attribute values, determined by the type of operation and a constant value (scalar) [2].

Overlay operations. An overlay operation generates a new layer (output layer) as a function of two or more input layers. For raster data, the overlay procedures require that the input data layers have a similar pixel size. This can be achieved by re-sampling the input data [2].

Connectivity operations. For raster data, the term connectivity describes the linkage between two pixels, that is, whether or not two pixels are connected, and if connected, the kind of connection involved. A distinguishing feature of connectivity functions is that they accumulate the values over the area being traversed (Aronoff 1989) in [3]. The connectivity functions include operations such as:

- Proximity
- Buffering
- Spread
- Network analysis

Network analysis is a type of connectivity operation [3]. In raster-based GIS network, operations can be performed using the output layers of spread and proximity analysis [3]. For example, the proximity surface or cost surface can be combined with a layer containing a network and a pair of points to identify the shortest path between two points (cells).

Network operations can be applied in a wide range of applications [3]:

- Calculate shortest or quickest paths between two points in a network
- Assess the impact of alternative routes
- Allocate potential users to facilities.

Neighbourhood operations. This class of operations involves assigning values to a location according to the characteristics of the surrounding area.

Search operations require that the target locations and the neighborhood be specified. With these two parameters, an algebraic or statistical operation is applied to the locations within the window (Figure 2.9 - Neighbourhood Window). The resulting value is assigned to each location in the neighbourhood.

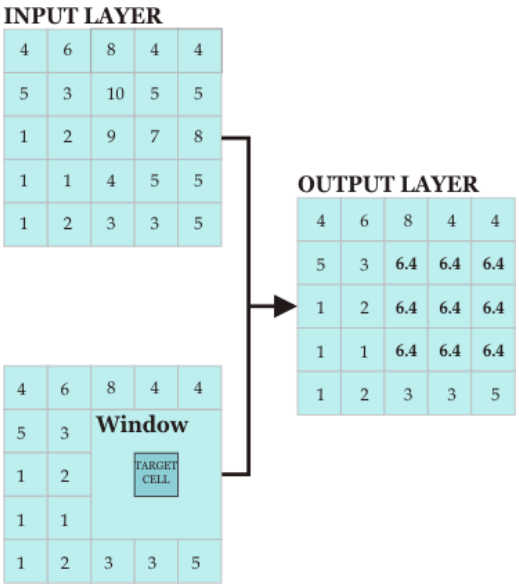


Figure 2.9 - Neighbourhood Window [3]

Point/line-in-polygon operations determine whether points/lines are inside or outside a polygon boundary. The attributes of these points/lines are identified as being within the polygon and can then be processed by displaying on a map, computing statistics of attribute values, listing attribute values in tabular form [3].

Surface operations involve calculating topographical characteristics such as slope and aspect from a digital elevation model. Slope is the rate of change of elevation expressed in degrees or percentage. Aspect is the direction in which a topographic slope faces, usually expressed in terms of degrees from north. These two characteristics of a surface at a given location (cell) can be determined by fitting a plane to the elevation values of neighbouring cells (Aronoff 1989) in [3].

2.8 Spatial Multi Criteria Decision Making

Spatial Multi-Criteria Decision Making (SMCDM) is different to conventional Multi-Criteria Decision Making (MCDM) as it requires both data on criterion values as well as its location [3]. The data are processed using GIS and MCDM techniques in order to obtain information. This information is then used to make a decision.

A spatial multi-criteria decision problem involves a set of geographically defined alternatives that have to be ordered so that the preferred alternative may be selected. The results of the decision making process depends on the spatial arrangement of the input criteria. In GIS terminology, the alternatives are a collection of point, line, and areal objects, to which criterion values are attached.

"Multicriteria decision making is more complex than that based on a single criterion because it is difficult to find an alternative that dominates all others with respect to all criteria" [3]. Spatial decision problems often involve a mixture of quantitative and qualitative information on evaluation criteria.

"The complexity of spatial decision problems depends on the number of people involved in the decision-making process (Massam 1988; Malczewshi 1996)" in [3]. The problem of locating a public facility such as a waste disposal site, trash incinerator facility, or nuclear power plant that the public perceives to be noxious or hazardous provides a good example of types of decisions involving location conflicts. Several communities may need such a facility but may have trouble finding a host community because of the NIMBY (not in my backyard) syndrome. Some groups may be in favour of locating a facility at a given site; others may prefer locating the facility elsewhere; still others may not be in favour of locating such a facility anywhere [2].

2.8.1 Information and Decision Making

"The process of converting data to information adds extra values to the original data (Cassettari 1993)" in [3]. During the decision-making process, the original data are interpreted and analyzed to produce information useful to decision makers. In this process the data are progressively converted into information about the decision problem. The decision problem determines the need and the nature of the information required. Malczewski [3] describes the concept of hard and soft information also referred to as objective and subjective information, respectively. Hard information is derived from reported facts, quantitative estimates and systematic option surveys e.g., census data, remote-sensing data, meteorological surveys. Soft information represents the opinions (preferences,

priorities, judgments, etc.) of decision makers, based on intuition, ad hoc surveys, questionnaires, comments, and similar sources. Soft information is used in the decision making process because social values and political considerations also enter into the realm of the decision maker. Any spatial decision making must consider a mix of hard and soft information. "*Central to spatial decision making is the way in which these two types of information are combined as well as the right balance between the amounts of hard and soft information used in the decision making process"* [3].

Both hard and soft information may involve a degree of uncertainty. Spatial decision-making is typically surrounded by uncertainty [3]. Information reduces uncertainty. Decision problems can be arranged on a scale ranging from predictable situations (perfect information) to situations that cannot be predicted (no information). The former is referred to as certainty or a deterministic situation the latter is referred to as a decision problem under uncertainty. The decisions under uncertainty can be further categorized into decisions involving stochastic information and imprecise information. This classification leads to the distinction between stochastic (probabilistic) and fuzzy decisions. Thus, depending on the quantity and type of information available in the decision-making process, three broad categories of spatial decision problems can be distinguished: deterministic, stochastic, and fuzzy [3].

Any decision making process can be structured into the following 3 major phases [3]:

- Intelligence Phase (is there a problem or an opportunity for change?)
- Design Phase (what are the alternatives?)
- Choice Phase (which alternative is best?)

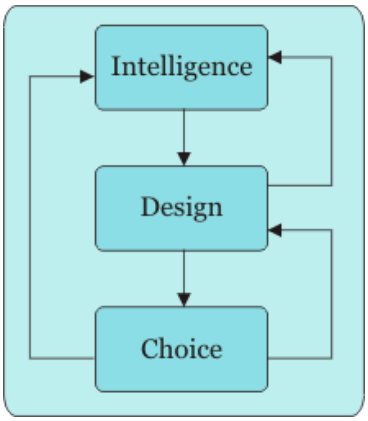


Figure 2.10 - Decision Phases [3]

The three phases in the decision making process require different types of information [3]. The phases do not follow a linear path and it may be necessary to loop back to a previous stage.

The above 3 phases can be further divided into a number of activities to form a process that starts with a decision problem and ends with recommendations. The sequences in which the activities are undertaken will affect the quality of the decision. Two of the major approaches to organizing the sequence of activities in the decision-making process are [3]:

- the alternative-focus approach, which focuses on the generating of decision alternatives,
- the value-focused approach, which uses the values (evaluation criteria) as the fundamental element of the decision analysis.

The framework shown in Figure 2.11 - Phase Model proposed by Malczewski [3] is based on the value-focused approach and integrates the phase model of decision making and the major elements of MCDM.

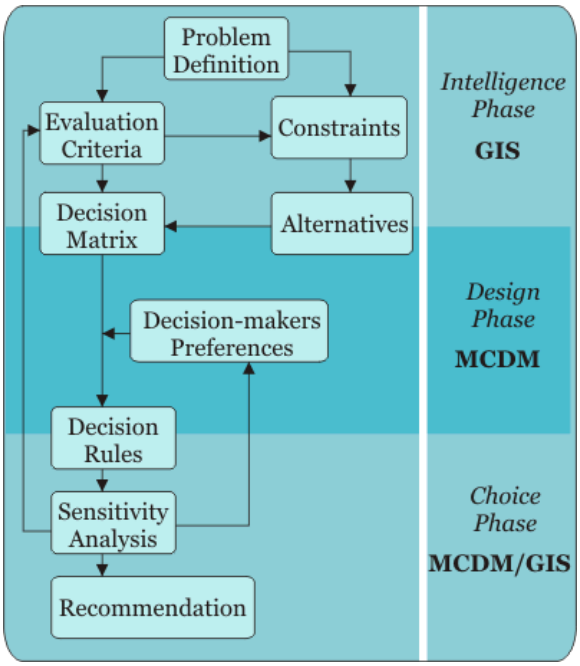


Figure 2.11 - Phase Model [3]

2.8.2 Intelligence Phase

The process of decision-making begins with the recognition of the problem. "*A spatial decision problem is the difference between the desired and existing state of a real-world geographical system"* [3]. During the intelligence phase raw data are obtained, processed, and examined for clues that may identify opportunities or problems. Data acquisition, storage, retrieval, and management functions convert the real world decision situation into the GIS database. Real world entities should be observed, selected, filtered, classified, and recorded as data items. Assumptions should be made as to which items are relevant to the spatial decision problem. Consideration must be given to the usefulness, timeliness, accuracy, reliability, and flexibility of data in terms of spatial disaggregation or aggregation. Once the spatial decisions have been identified, the data can be manipulated and analyzed to obtain information about the decision problem. "*Exploratory data analysis plays a major role in the intelligence phase*" [3].

"Adequate support for the intelligence phase of decision making is provided by current GIS systems" [3]. GIS systems offer unique methods to tackle problems

traditionally associated with data collection and analysis more efficiently and effectively. They play a vital role at the initial stage of spatial decision making by storing and managing a large amount of spatial data and information. GIS can also effectively present information to decision makers that would be difficult to analyze if presented in the form of a tabular report [3].

Evaluation Criteria

This step involves specifying [3]:

(1) a comprehensive set of objectives that reflects all concerns relevant to the decision problem, and
(2) measures called attributes for achieving those objectives.

Defining the Set of Evaluation Criteria

"The general rule for selecting *evaluation criteria is that they should be identified with respect to the problem*" [3].

Two tendencies can be distinguished in defining the set of evaluation criteria (Ozernoi and Gaft 1977; Munda 1995) in [3]. First, the number of evaluation criteria is defined in such a way that the decision model describes the problem situation as closely as possible. This may lead to many criteria being included in the decision model. Secondly, the problem situation can be described by a small number of criteria. This may lead to an oversimplification of the decision problem. "*This oversimplification is usually related to data availability and data quality*" [3].

"The procedures for selecting a set of attributes should be based on the desirable properties of attributes. Both individual attributes and a set of attributes should possess some properties to adequately represent the multi criteria nature of the decision problem (Keeney and Raiffa 1976)" in [3]. A set of attributes should be comprehensive and measurable and cover the following [3]:

- operational (they can be used meaningfully in the analysis),
- decomposable (they can be broken into parts to simplify the process)

- non-redundant (they avoid problems of double counting)
- minimal (the number of attributes should be kept as small as possible).

Techniques for Selecting Criteria

Even though the desirable properties of objectives and attributes can provide guidelines for selecting a set of evaluation criteria there are no universal techniques available for determining a set of criteria [3]. A set of criteria depends on the particular problem being analyzed and is therefore problem specific. The criteria used for evaluating sites for nuclear plant location analysis, for example, will be different from the set of criteria involved in a substation location problem. Irrespective of the nature of the decision problem, the procedure for identifying a set of evaluation criteria should be a multistep iteration process [3].

The Delphi method is probably the most popular and versatile technique used to obtain opinions.

"The Delphi method is a unique way to develop a set of evaluation criteria where no factual data exists. A group of experts in the field of interest is identified and each person is sent a questionnaire. The experts are kept apart and are unknown to each other. The independent nature of the process ensures that the responses are truly independent and not influenced by others in the group. This forecasting method involves an iterative process in which all the responses and supporting arguments are shared with the other participants, who then respond by revising or giving further arguments in support of their answers. After the process has been repeated several times, a consensus develops as to which criteria should be included in the set of objectives and attributes for a particular decision problem. The heart of the Delphi method is the structure that relates all the contributions made by the individuals in the group and which produces a group view or perspective. For this reason, this approach is particularly suitable for group decision-making problems" [3].

A danger in using opinions rather than facts is that individuals may let their personal feelings influence what they know to be fact. Even when objective

sources can be called upon, opinions may offer valuable insight into the decision problem and should therefore not be discarded as a bad source of advice. A combination of this approach together with the examination of relevant literature and/or analytical study should be used for designing a set of evaluation criteria (MacCrimmon 1969; Keeney and Raiffa 1976) in [3].

Criterion Maps

Each criterion that will be used in evaluating corridor selection alternatives can be represented by a separate map layer in the GIS database [3]. The map layers are referred to as criterion maps. A criterion map can be either a factor criterion map or a constraint criteria map [11]. A factor criterion map represents the spatial distribution of a single attribute. The attribute is a measure of the degree to which the associated objective is achieved. A constraint criteria map represents restrictions imposed on the set of factors and is used to eliminate from consideration areas characterized by certain attributes.

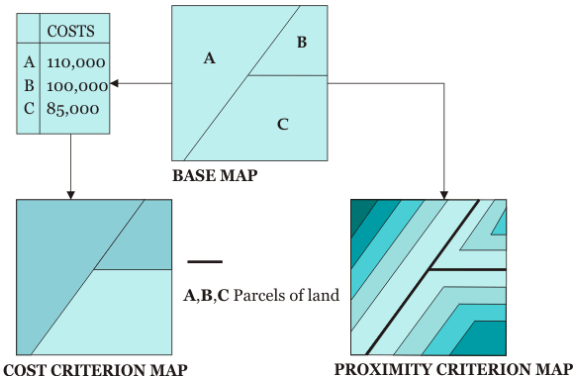


Figure 2.12 - Example Criterion Map [3]

GIS functions are used to create the criterion maps, these functions include the functionality that caters for geographical data input (acquisition, reformatting, georeferencing, compiling, and documenting relevant data), storage of attribute or spatial data, manipulation / analysis to derive information and output.

Scales of Measurement

For an attribute to be useful, a scale should be used to describe its relative levels [3]. Attributes can be measured on qualitative and quantitative scales and as such criterion maps can be classified into corresponding scales of measurement as either qualitative or quantitative criterion maps [3].

Scale	Map Type
Qualitative	soil types, vegetation types, settlement types
Quantitative	digital elevation model, household income, proximity maps

In the context of decision, making a distinction can be made between natural and constructed scales (Figure 2.13) and therefore criterion maps can be classified as either natural-scale criterion maps or constructed-scale criterion maps [3].

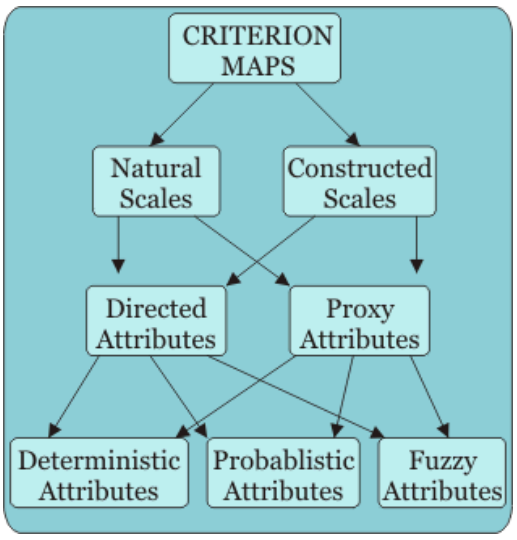


Figure 2.13 - Classification of criterion maps [3]

Natural scales are those that have been established over time and enjoy common usage and interpretation. Distance in kilometres is a natural attribute. Constructed scales are also sometimes referred to as subjective scales or subjective indices. Constructed scales such as the 'aesthetic impact' have no natural scale for measuring [3].

Both natural and constructed scales can be further subdivided into two categories: direct and proxy scales (Keeney and Raiffa 1976; Keeney 1980) in [3]. A direct scale measures the degree of achievement directly i.e. cost [3].

For some criterion, there is no obvious attribute to measure the level of achievement directly. In such a case, a proxy scale can be used. A proxy scale measures the degree of achievement indirectly. The proxy attributes provide the base for generating proxy-scale criterion maps. A proxy attribute may be related to the corresponding objective as a cause, a consequence of its achievement. An example of a proxy attribute is the ambulance response time being used as a proxy for the objective "minimize probability of death on arrival" [3].

It is usually easier to generate maps that represent natural and direct attributes than to generate constructed and proxy maps [3].

Deriving Standardised Criterion Maps

Attributes can be measured at various scales, to be able to perform multi-criteria analysis the values contained in the different criterion map layers have to be transformed to comparable units [2]. A number of techniques can be used to make criterion map layers comparable. Based on the information used to construct the criterion map layers they can be categorized as deterministic, probabilistic, or fuzzy [3].

Deterministic maps assign a single value to each object (point, line, polygon, or pixel) in a map layer. For deterministic criteria, there will be a deterministic relationship between an alternative and its consequences [3]. Linear scale transformation is the most frequently used deterministic method for transforming input data into standardised criterion maps [3]. Another way of deriving standardised criterion maps is to use value/utility functions. The value function method is applicable in deterministic situations while the utility function method is appropriate for decision situations involving uncertainty [3].

Another way of generating standardised criterion maps is to use the probability concept. The probabilistic approach can be based on objective, subjective, and revisited probabilities [3]. The fuzzy membership function approach can also be used to generate standardised criterion map layers [11].

2.8.3 Design Phase

"The design phase involves inventing, developing, and analyzing a set of possible solutions to problems identified in the intelligence phase" [3]. A formal model which is a simplified representation of reality is used to support a decision maker in determining a set of alternatives. Reality is too complex to copy precisely. In most instances, this complexity is actually irrelevant to the specific problem and therefore a simplified representation can be used [3].

"Most commercially available GIS's lack the kind of spatial analysis and modelling required by decision maker's" [3]. The capabilities of GIS's for generating a set of alternative decisions are mainly based on the spatial relationship principles of connectivity, contiguity, proximity, and the overlay methods.

"Overlay operations can be used for identifying suitable areas for new development but when the selection needs to consider conflicting evaluation criteria the overlay functions do not provide enough analytical support because of limited capabilities for incorporating the decision makers preferences into the GIS-based decision making process further consideration is that the complexity of relationships in some spatial decision problems cannot be represented cartographically, or the cartographical representation may be cumbersome and take time to construct or manipulate. GIS systems are not flexible enough to accommodate variations in either the context or the process of spatial decision making" [3].

Multi-Criteria Decision Making (MCDM)

"Decision-making involves a set of systematic procedures for analyzing complex decision problems. The basic strategy is to divide the decision problem into small, understandable parts; analyse each part, and integrate the parts in a logical manner to produce a meaningful solution" [3].

During the corridor selection process Multi-Criteria Decision Making techniques are used to select and weight criterion that need to be evaluated. These techniques can partially or completely rank the alternatives [12].

Elements of MCDM

MCDM problems involve six components [12]:

- a goal or a set of goals the decision maker (interest group) attempts to achieve;
- the decision maker or group of decision makers involved in the decision-making process along with their preferences with respect to evaluation criteria;
- a set of evaluation criteria (objectives and or attributes) on the basis of which the decision makers evaluate alternative courses of action;
- the set of decision alternatives, that is, the decision or action variables;
- the set of uncontrollable variables or states of nature (decision environment); and
- the set of outcomes or consequences associated with each alternative-attribute pair.

The central element of this structure is a decision matrix consisting of a set of columns and rows (Pitz and McKillip 1984) in [3]. The matrix represents the decision outcomes for a set of alternatives and a set of evaluation criteria.

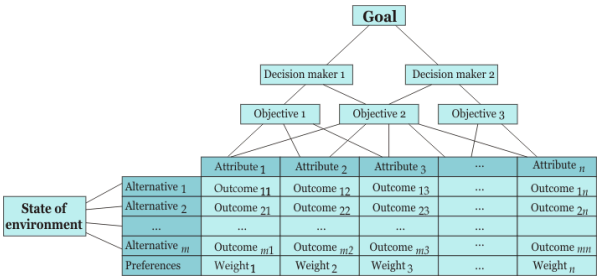


Figure 2.14 - Elements of MCDM [3]

Individual vs. Group Decision Making

Many spatial decisions are made by multiple decision makers rather than an individual decision maker. *The distinction between individual and group decision making rests less on the number of people involved than on the consistency of the group's goals, preferences, and beliefs. If we can assume a single goal-preference-belief structure, we are dealing with individual decision making, regardless of the number of people actually involved [3].*

Criterion Weights

"A weight can be defined as a value assigned to an evaluation criterion that indicates its importance relative to other criteria under consideration. The larger the weight, the more important is the criterion" [3].

The purpose of the criterion weights is to express the importance of each criterion relative to the other criteria being evaluated. The decision maker's preferences are incorporated into the decision model by assigning relative weights to each criterion. Using the set of alternatives, attributes, and associated weights, the input data can be organized in the form of a decision matrix [3].

A number of methods exist to rank and weight criteria. Four of the methods that are used in spatial multi-criteria evaluation are listed below.

Ranking Methods

According to Malczewski [3] the simplest way of gauging the importance of weights is to arrange them in rank order. The criteria can be ordered in either straight or inverse ranking. Once the ranking has been determined, a number of methods such as rank sum or rank exponent can be used to generate the numeric weight.

Rating Methods

In the rating methods the decision maker is required to estimate weights on a predetermined scale [3]. A number of methods such as the point allocation or ratio estimation procedure can then be used to assign weights to each criterion.

Trade-off Analysis Method

Malczewski [3] describes the Trade-off Analysis Method as a method that makes use of direct assessments of the trade-offs that a decision maker is willing to make between pairs of alternatives. The relationships between the criteria can be used to calculate the weights.

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed by Saaty [13]. This method involves pair-wise comparisons to create a ratio matrix. It takes as an input the pair-wise comparisons and produces the relative weights as output. The weights are determined by normalizing the eigenvector associated with the maximum Eigen value of the reciprocal ratio matrix [3].

The procedure consists of three major steps: generation of the pair-wise comparison matrix, the criterion weights computation, and the consistency ratio estimation [3].

1. **Development of the pair-wise comparison matrix.** The method employs an underlying scale with values from 1 to 9 to rate the relative preferences for two criteria

Table 2.4 - AHP Rating Scale [13]

	Value	Relative Preference
Less Important	1/9	extremely
	1/7	very strongly
	1/5	strongly
	1/3	moderately
	1	equally
More Important	3	moderately
	5	strongly
	7	very strongly
	9	extremely

2. Computation of the criterion weights. This step involves the following operations [3]:

(a) sum the values in each column of the pair-wise comparison matrix;

(b) divide each element in the matrix by its column total (the resulting matrix is referred to as the normalized pair-wise comparison matrix); and

(c) compute the average of the elements in each row of the normalized matrix, that is, divide the sum of normalized scores for each row by the number of criteria. These averages provide an estimate of the relative weights of the criteria being compared

3. Estimation of the consistency ratio. In this step a determination is made as to whether the comparisons are consistent [3]. It involves the following operations: (a) determine the weighted sum vector by multiplying the weight for the first criterion times the first column of the original pair-wise comparison matrix, then multiply the second weight times the second column, the third criterion times the third column of the original matrix, finally, sum these values over the rows; and (b) determine the consistency vector by dividing the weighted sum vector by the criterion weights determined previously.

Values for two more terms, lambda (λ) and the consistency index (*CI*) need to be calculated. The value for lambda is simply the average value of the consistency vector:

The calculation of *CI* is based on the observation that λ is always greater than or equal to the number of criteria under consideration (n) for positive, reciprocal matrixes, and λ = n if the pair-wise comparison matrix is a consistent matrix . Accordingly, λ - n can be considered as a measure of the degree of inconsistency. This measure can be normalized as follows:

$$CI = \frac{\lambda - n}{n - 1} \qquad \text{..... Equation 1}$$

The *CI* term, referred to as the consistency index, provides a measure of departure from consistency. We can calculate the consistency ratio (*CR*), which is defined as follows:

$$CR = \frac{CI}{RI} \qquad \text{..... Equation 2}$$

where *RI* is the random index, the consistency index of a randomly generated pair-wise comparison matrix. *RI* depends on the number of elements being compared. The consistency ratio (*CR*) is designed in such a way that if *CR* < 0.10, the ratio indicates a reasonable level of consistency in the pair-wise comparisons; if, however, CR ≥ 0.10, the values of the ratio are indicative of inconsistent judgments. In such cases one should reconsider and revise the original values in the pair-wise comparison matrix. *RI* is selected from a listed of values that is part of the AHP.

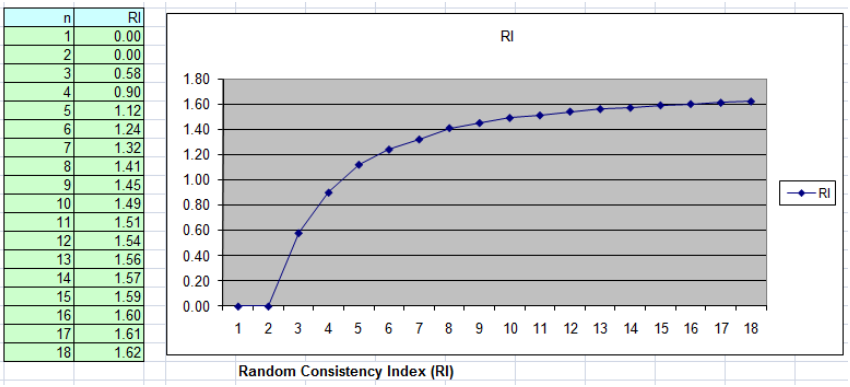


Figure 2.15 – Random Consistency Index (RI) [3]

The AHP can be criticized for its meaningfulness of responses to the underlying questions (Goodwin and Wright 1998) in [3]. The questions simply ask for the relative importance of evaluation criteria without reference to the scales on which the criteria are measured. This fuzziness may mean that the questions are interpreted in different, and possibly erroneous, ways by decision makers [3]. One advantage of the paired-comparison method is that only two criteria have to be considered at a time [3]. If many criteria are being compared, the matrix may get very large. With n criteria, it involves n(n - 1)/2 comparisons.

This method has been tested theoretically and empirically for a variety of decision situations, including spatial decision making (Lai and Hopkins 1995; Siddiqui et al. 1996; Malczewski et al. 1997a) in [3].

Comparing the Methods

Table 2.5 summarizes the major features of the four methods for assessing criterion weights. Although some of the summary statements are oversimplifications of complex issues, it is suggested that they provide a guideline for choosing a method for weight assessment [3]. Which method to use would depend on the compromises one is willing to make between ease of use, accuracy, the degree of understanding on the part of the decision maker, and the theoretical foundation underlying a given method; the availability of computer software; and the way the method can be incorporated into GIS-based multi-criteria decision analysis [3]. *Empirical applications suggest that the pair-wise comparison method is one of the most effective techniques for spatial decision making including GIS-based approaches (Eastman et al. 1993; Malczewski et al. 1997a)* in [3]. Based on an experiment, Lai and Hopkins (1995) in [3] demonstrated that the pair-wise comparison method was insignificantly different from the trade-off method in effectiveness. They also found that the former method was better than the trade-off approach with respect to time.

Table 2.5 - Comparison of Rating Methods [3]

	Method			
Feature	**Ranking**	**Rating**	**AHP**	**Trade-off Analysis**
Number of judgments	*n*	*n*	*n(n-1)/2*	*<n*
Response scale	*Ordinal*	*Interval*	*Ratio*	*Interval*
Hierarchical	*Possible*	*Possible*	*Yes*	*Yes*
Underlying theory	*None*	*None*	*Statistical / heuristic*	*Axiomatic / deductive*
Ease of use	*Very easy*	*Very easy*	*Easy*	*Difficult*
Trustworthiness	*Low*	*High*	*High*	*Medium*
Precision	*Approximations*	*Not precise*	*Quite precise*	*Quite precise*

2.8.4 Choice Phase

The choice phase involves selecting a particular alternative from those available [3]. During this phase, each alternative is evaluated and analyzed in relation to others in terms of a specified decision rule. The rule is used to rank the alternatives according to the decision maker's preferences [3].

Critical for the use of GIS in the choice phase is the capability of incorporating decision makers' preferences in the decision-making process [3]. In general, GIS systems do not provide a mechanism for representing choice and priority in the context of evaluating conflicting criteria and objectives [3]. They do not allow the decision maker the flexibility to change the importance of evaluation criteria. This restriction makes GIS a very static modelling environment and thus reduces its scope as a decision support tool [3].

Decision Rules

"Decision rules are implemented by making use of MCDM procedures that utilize geographical data and the decision maker's preferences to manipulate the data to define a relationship between the input maps and the output map. The procedures aggregate the input multi-dimensional geographical data and information into the uni-dimensional values of the output" [3].

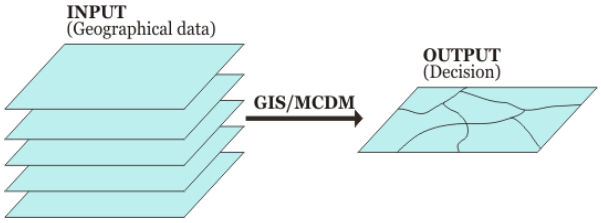


Figure 2.16 - GIS Layers in a Spatial MCDM Problem [3]

The one-dimensional measurements (geographic data layers) and judgments (preferences and uncertainty) have to be integrated to provide an overall assessment of the alternatives [3].

Multi Attribute Decision Rules

The aim of MADM analysis is to choose the best or the most preferred alternative, to sort out alternatives that seem "good" and/or to rank the alternatives in descending order of preference [3]. There are numerous decision rules that can be used for tackling the MADM problem.

Simple additive weighting (SAW) methods are the most often used techniques for tackling spatial multi-attribute decision-making [1]. These techniques are also referred to as weighted linear combination (WLC) or scoring methods. They are based on the concept of a weighted average. The decision maker directly assigns weights of "relative importance" to each attribute. A total score is then obtained for each alternative by multiplying the importance weight assigned for each attribute by the scaled value given to the alternative on that attribute, and summing the products over all attributes. When the overall scores are calculated for all the alternatives, the alternative with the highest overall score is chosen. Formally, the decision rule evaluates each alternative, A_i, by the following formula [3]:

$$A_i = \sum_j w_i x_{ij} \quad \text{---------- Equation 3}$$

where X_{ij} is the score of the ith alternative with respect to the jth attribute, and the weight w_i is a normalized weight, so that $\sum w_j = 1$. The weights represent the

relative importance of the attributes. The most preferred alternative is selected by identifying the maximum value of A_i (i = 1,2, ... ,m).

The GIS-based SAW method involves the following steps [3]:

- Define the set of evaluation criteria (map layers) and the set of feasible alternatives.
- Standardise each criterion map layer.
- Define the criterion weights.
- Construct the weighted standardised map layers by multiplying standardised map layers by the corresponding weights.
- Generate the overall score for each alternative using the add overlay operation on the weighted standardised map layers.
- Rank the alternatives according to the overall performance score; the alternative with the highest score is the best alternative.

The SAW methods can be operationalised using any GIS system having overlay capabilities [3]. The overlay techniques allow the evaluation criterion map layers (input maps) to be aggregated to determine the composite map layer (output maps) [3].

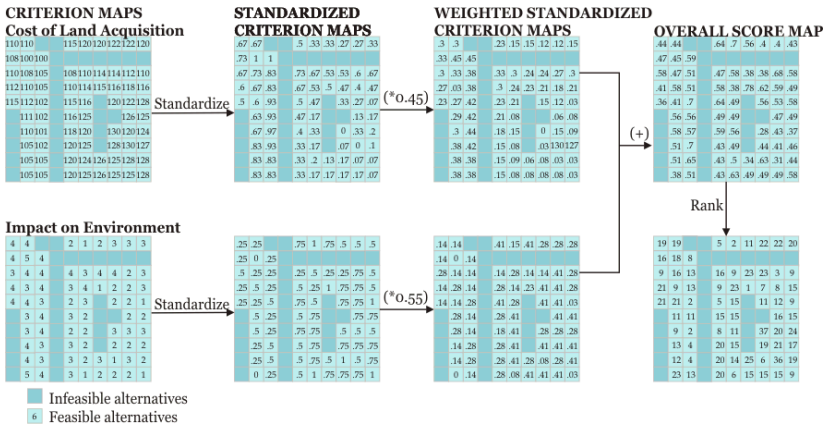


Figure 2.17 - Overlaying Criterion Maps [3]

This technique can be criticized for its ignorance of the definition of the units of measurement [3]. Since the weights are multiplied by the ratings for attributes to

obtain a score for an alternative, they depend on the units used for each attribute. Thus, the greatest disadvantage of the SAW methods is that they tend to be ad hoc procedures with little theoretical foundation to support them [3]. However, because they are easy to use, SAW methods are widely applied in real-world settings (Massam 1988; Janssen 1992; Eastman et al. 1993) in [3].

Recommendation

"The end result of a decision-making process is a recommendation for future action" [3]. The recommendation should [3]:

(1) Be based on the ranking of alternatives and sensitivity analysis.
(2) It may include the description of the best alternative or a group of alternatives considered candidates for implementation.
(3) Use Visualization techniques in presenting and communicating the results to decision makers and interest groups.
(4) The solutions to spatial multi-criteria decision problems should be presented in both decision (geographical) space and criterion outcome space.

Each stage of the spatial multi-criteria analysis involves both GIS and MCDM methodologies. The stages differ in terms of the degree to which these two methodologies are used. In the earlier stages, GIS techniques play the major role, while in the latter stages, MCDM techniques are of major importance [3].

2.9 Multi Criteria Spatial Decision Support Systems

"*A SDSS can be defined as an interactive, computer based system designed to support a user in achieving a higher level of effective decision making while solving a semi-structured spatial decision problem*" [3]. Desham (1991) in [3] suggests a SDSS should have the following characteristics:

- An explicit design to solve ill-structured problems
- Powerful and easy-to-use user interface
- Ability to combine analytical models flexibly with data
- Ability to explore the decision space by building alternatives

- Capable of supporting a variety of decision making styles
- Allowing interactive and recursive problem solving
- Provide mechanisms for spatial data input
- Allow representation of the spatial relations and structures
- Include the analytical techniques of spatial analysis
- Provide output in a variety of spatial forms including maps

The way that Multi Criteria Spatial Decision Support Systems (MC-SDSS) integrate GIS capabilities and MCDM techniques depends on the decision making process to be modelled but in general the frameworks consists of the following 4 components:

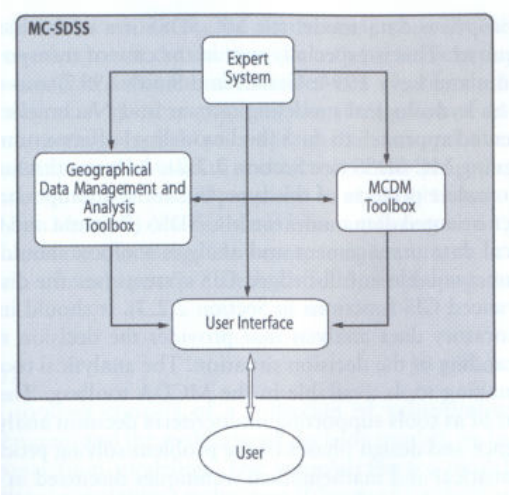


Figure 2.18 Components of a MC-SDSS [3]

- **GIS database and Analysis Toolbox**

  Exploratory data analysis, statistical analysis and simulation etc. The data related tasks such as storing, maintaining, retrieving data from the database and extracting data from various sources including providing access to data in the appropriate format is performed by the data subsystem.

- **Multi-criteria Decision Toolbox**

  Tools for generating value structure, preference modelling and multi attribute decision making.

- **Expert System**

  Artificial intelligence to assist the decision maker in using expert knowledge.

- **User interface**

  The user interface is that part of the SDSS that allows the user to input data, make selections and retrieve the results.

2.10 Route Selection in GIS

Least cost path analysis has been part of GIS for some time. Varying levels of support for least cost path analysis exists in many GIS systems. The process of selecting a least cost path is different in the GIS systems that have such functionality.

2.10.1 Determining a Least Cost Path in ArcGIS

To determine a least cost path using raster in ArcGIS 9 the Spatial Analyst extension is required. With this extension it is possible to manipulate and process the input raster files to determine a suitability map. The suitability map is derived by combining a number of criterion raster files by means of a weighted overlay. An external process such as the AHP can be used to determine the ranking of each criterion. The weights determined by the external process can be transformed to the weights required by the weighted overlay process. Any of a number of routing functions can be used to determine the least cost path.

2.10.2 Determining a Least Cost Path in IDRISI

IDRISI Taiga has extensive support for determining a least cost path. This support includes fundamental GIS functionality as well as support for spatial multi-criteria

decision-making and fuzzy membership functions. The process of selecting a least cost path described by Eastman [2] was adopted as the preferred method of selecting a corridor in this research. The process is described in more detail in 4.1.8 System Requirement 8 – Selection Model on page 64.

3 Research Methodology

3.1 Research Question

A quantitative spatial decision support model has been constructed by combining spatial analysis (GIS) and a multi criteria decision making method. This method ranks and prioritises environmental, social and engineering criteria. ***How effectively can this decision support model assist expert decision makers in selecting a corridor for an overhead electrical transmission line between two substations?***

3.2 Research Hypothesis

The research hypothesis is that a decision support system will assist expert decision makers to identify areas that are more suitable for locating an overhead electrical transmission line corridor between 2 substations and enable them to perform scenario analysis by considering various alternatives.

3.3 Approach to Research

The methodology followed in this research involved reviewing relevant literature and obtaining expert opinion on the requirements for an OETL Corridor Selection SDSS. Using the requirements received from the experts, a process to select corridors was assembled. A software implementation of the process was built using IDRISI Taiga and the effectiveness of the process evaluated by exploring three scenarios in an effort to achieve a balance between development and the protection of the environment.

This research was done in three stages. Each stage addressed different aspects that are discussed in more detail in subsequent chapters.

3.3.1 Stage 1 - Determine Requirements for a Corridor Selection Spatial Decision Support System

The process of selecting a corridor for an OETL requires input from different disciplines. Traditionally representatives from each of these disciplines would contribute to the corridor selection process at different stages in the process. To develop the SDSS it was necessary to identify the requirements up front to ensure that all the requirements were incorporated into the SDSS.

Meetings to determine the requirements for a SDSS to select corridors for an OETL were held with representatives (SME) from the following disciplines/departments in Eskom:

- Transmission GIS Department
- Transmission Environmental Department
- Eskom Corporate GIS Department (ESIGIS)
- Central Region Land Development
- Central Region Planning
- Central Region Project Engineering

3.3.2 Stage 2 - Develop a Selection Methodology

In stage 2 a selection methodology that conjoined a ranking/weighting method, corridor selection and spatial analysis functions to determine the corridor and present the results was developed. A prototype SDSS based on the selection methodology was built and used to evaluate the selection methodology.

The selection methodology addressed the requirements identified by the SME's. The prototype included a method to rank and weight the criteria identified by the SME's, a mechanism to determine a cost-of-passage surface from the weighted criteria and least cost path functions to determine a corridor. The prototype is discussed in chapter 4.

3.3.3 Stage 3 - Evaluate the Selection Methodology

The prototype was used to evaluate 3 scenarios. The output generated by the prototype was presented to the SME's who evaluated if the results were acceptable and usable. The evaluation of the scenarios is discussed in chapter 5 and the results in chapter 6.

The prototype was presented to the following interest groups to gather feedback and to create awareness of the possibility of using the technology (Appendix A).

- Transmission Right of Way Negotiators
- Members of the South African Rights of Way Association at their Annual Conference
- Eskom Corporate GIS Steering Committee
- Eskom Corporate GIS Department (ESIGIS)

ESIGIS suggested that the selection methodology be further evaluated as part of a pilot project (3.4).

In this research it was assumed that the information and evaluation given by the environmental and engineering experts was correct.

3.4 Pilot Project

Within Eskom, corridor selection is primarily the responsibility of the Lands and Rights department. ESIGIS initiated a pilot project to establish if the SDSS could be used to derive a suitability map that would assist in determining a corridor for an OETL.

A project charter (Appendix B) was compiled to establish the terms of reference for the project. Three workshops were held with representatives from Eskom's Northern Region Land Development Department to determine the criteria and parameters that would be used in the model. The representatives are considered experts (SME) in this field and have years of experience in selecting routes for

OETL's. The concepts, techniques and some of the technologies available when selecting a corridor using GIS and multi-criteria decision analysis was presented to the project team. At the workshops the SME's were tasked with identifying criteria for a spatial decision support system that could assist them in selecting corridors. The selection methodology that was modelled in IDRISI Taiga as part of this research was modelled in ArcGIS 9.1 and used to evaluate the criteria and a draft report compiled. The Pilot Project has not been completed.

3.5 Summary

Chapter 3 introduced the research question and research methodology. The research methodology included consulting SME's to determine the requirements for the Corridor Selection SDSS. These requirements are explained in the next chapter.

4 Selection Methodology

In this chapter, the process of selecting a corridor for an OETL is explained. Paragraph 4.1 deals with the requirements for an OETL Corridor Selection SDSS by discussing each requirement in relation to the requirement identified by the SME's. The proto type SDSS assembled to address these requirements is discussed in paragraph 4.2.

4.1 SDSS Requirements

Table 4.1 below is a summary of the SME's requirements for an OETL Corridor Selection SDSS. These requirements were treated as user requirements for a SDSS. Each of the SME requirements was evaluated. After evaluating the SME's requirements, they were reformulated into system requirements. Concepts, methods and approaches to address each system requirement were evaluated and an appropriate solution selected. The solutions were then assembled to form an SDSS.

Table 4.1 - Subject Matter Experts Requirements for a SDSS

No {Column A}	**Description of Requirement** {Column B}
1	Consider multiple criteria simultaneously.
2	GIS based.
3	Avoid environmentally sensitive areas.
4	Select a corridor.
5	Consider the following criteria: Existing Network Roads Rivers Dams Slope Wetlands Farm Boundaries Railway Lines Land Use
6	Limit the corridor length to 120% of the shortest distance.
7	Easy to execute.
8	Results to be presentable at public forums.

Table 4.2 below is a summary of the system requirements that were derived from the requirements identified by the SME's. In **Table 4.2** the No column {Column A} refers to the paragraph that discusses that requirement. The SME Requirement {Column C} column refers to the No column {Column A} in **Table 4.1**.

Table 4.2 -Technology and Functionality Requirements

No {Column A}	**SDSS Requirement** {Column B}	**SME Requirement** {Column C}	**Selected Technology / Functionality** {Column D}
1	Spatial Data Structure	5	Raster
2	Fundamental GIS Functions	1,2,8	IDRISI Taiga
3	Weight Criteria	3	AHP Spreadsheet MCE Function
4	Standardise Factors	1	Fuzzy Functions Lineras Function Distance Function Surface Function Reclass Function
5	Evaluate Multiple Criteria Spatially	1,3	WLC
6	Determine a Least Cost Route	4	IDRISI Taiga Assign Function Pointras Function Cost Function Pathway Function Linevec Function
7	Preferred Route	6	AHP
8	Selection Model	7	IDRISI Taiga
9	3D Visualisation	8	IDRISI Taiga 3D Physical Model

4.1.1 System Requirement 1 - Spatial Data Structure

The criteria to be evaluated during the corridor selection process identified by the SME's could be loaded into a GIS as either raster or vector data. The raster data structure was selected rather than the vector data structure due to its suitability to represent continuously varying data such as slope. The fact that the grid of data is better for modelling and interpolation [3] also contributed to the decision.

Other factors taken into account in selecting the raster data structure were:

- Raster data can easily be converted to vector data and visa versa.
- The fact that raster data has a fixed resolution was not a concern as all criteria raster's would be re-sampled.
- The coarsest resolution could be adopted.
- The volume of data could be managed as the cost of disk space was of lesser concern than it might have been a number of years ago.
- Raster is suited to area based spatial analysis.

4.1.2 System Requirement 2 - Fundamental GIS Functions

IDRISI Taiga was selected as the platform on which to develop the prototype SDSS as it provided the required level of support for raster based fundamental GIS functionality and multi-criteria decision-making.

The fundamental GIS functions that were required included functions to input the spatial data; manipulate the spatial data and output the results as either maps or tabular reports.

IDRISI Taiga is an integrated GIS and Image Processing software solution providing nearly 300 modules for the analysis and display of digital spatial information. IDRISI Taiga provides [17]:

- A complete GIS analysis package for basic and advanced spatial analysis, including tools for surface and statistical analysis, decision support, and change and time series analysis
- A complete Image Processing system with the most extensive hard and soft classifiers in the industry, including machine learning classifiers such as neural networks and classification tree analysis, as well as image segmentation for classification
- Integrated modelling environments including the Earth Trends Modeller for image time series of environmental trends and Land Change Modeller for land change analysis and prediction.
- Complete utilities for import and export.

Parameters are input into IDRISI Taiga via user friendly forms.

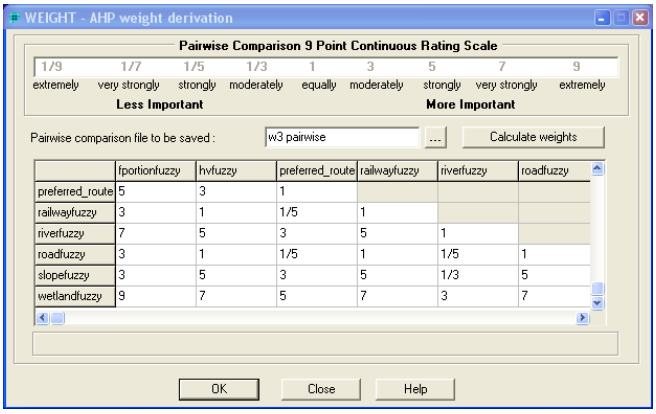


Figure 4.1 – Example AHP Input Dialog

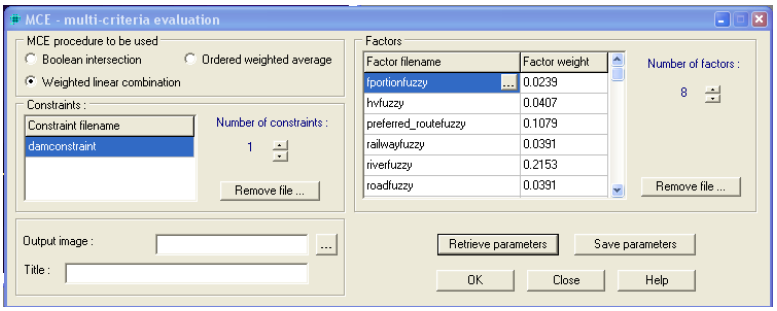


Figure 4.2 – Example MCE Input Dialog

4.1.3 System Requirement 3 - Weight Criteria

A combination of SME opinions, objective sources and relevant literature was used to identify the criteria with which to evaluate the corridor selection process. In the corridor selection model, a criterion was considered either a constraint or a factor with a Boolean raster representing each constraint and a continuous binary raster representing each factor.

A constraint is a criterion that removes from consideration the pixels representing unsuitable areas. A factor on the other hand is a criterion that either enhances or detracts from the suitability to locate a corridor at a particular location.

Each factor influences the decision to a different degree. The extent to which each factor influences the decision is controlled by allocating a weight to each factor.

The derivation of weights is thus a central step in the decision making process. A weight can be defined as a value assigned to a factor that indicates its importance relative to the other factors under consideration [11]. The larger the factor's weight the more important the factor.

Ecological, electrical, aesthetic and socio-economic considerations such as those listed in Table 4.3 plus the availability of the data were taken into account when selecting the criteria to be used in this research. Multiple related criteria were combined to form a new criterion by making use of the appropriate screening method and other fundamental GIS functions.

In the model, a spatial GIS raster layer that is on a similar scale in order to be comparable represents each criterion. The scale at which each criterion was evaluated is important and the attribute used was classified as deterministic, probabilistic or fuzzy using either a natural or a proxy scale.

A number of multi-attribute decision-making techniques that can partially or completely rank criteria were investigated. Table 2.5 on page 43 compares 4 of these ranking techniques. The analytic hierarchy process (AHP) [13] was selected as the preferred method for ranking the criteria (Table 4.3) in the selection model.

The fact that the AHP includes a mechanism to determine the level of consistency in the comparisons was considered a major advantage over other ranking methods and was the primary reason for incorporating it into the selection model.

Table 4.3 - Criterion selected for this research

Criterion	Criterion Type	Evaluation Scale
HV Network	Factor	Fuzzy
Road	Factor	Fuzzy
River	Factor	Fuzzy
Dam	Constraint	Fuzzy
Slope	Factor	Fuzzy
Wetland	Factor	Fuzzy
Farm Boundary	Factor	Fuzzy
Railway	Factor	Fuzzy

A spreadsheet was compiled based on Saaty's AHP [13] and this spreadsheet was used in the workshops to facilitate the process of obtaining the SME's opinion of which criteria to consider as well as comparing the criteria to determine the factor weights.

Weight Calculation

n =	8
lambda max	9.0313
consistency index (CI)	14.73%
consistency ratio (CR)	10.45%
RI	1.41

Reciprocal matrix

Criteria	Farm Boundary	HV Network	Preferred Route	Railway	River	Road	Slope	Wetland
Farm Boundary	1.00	0.33	0.20	0.33	0.14	0.33	0.33	0.11
HV Network	3.00	1.00	0.33	1.00	0.20	1.00	0.20	0.14
Preferred Route	5.00	3.00	1.00	5.00	0.33	5.00	0.33	0.20
Railway	3.00	1.00	0.20	1.00	0.20	1.00	0.20	0.14
River	7.00	5.00	3.00	5.00	1.00	5.00	3.00	0.33
Road	3.00	1.00	0.20	1.00	0.20	1.00	0.20	0.14
Slope	3.00	5.00	3.00	5.00	0.33	5.00	1.00	0.20
Wetland	9.00	7.00	5.00	7.00	3.00	7.00	5.00	1.00
Sum	34.00	23.33	12.93	25.33	5.41	25.33	10.27	2.27

Table 8. Random Consistency Index (RI)

n	RI
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

NORMALIZED MATRIX

Criteria	Farm Boundary	HV Network	Preferred Route	Railway	River	Road	Slope	Wetland	Sum	Weights: priority vector
Farm Boundary	0.029	0.014	0.015	0.013	0.026	0.013	0.032	0.049	0.193	**2.42%**
HV Network	0.088	0.043	0.026	0.039	0.037	0.039	0.019	0.063	0.355	**4.44%**
Preferred Route	0.147	0.129	0.077	0.197	0.062	0.197	0.032	0.088	0.930	**11.62%**
Railway	0.088	0.043	0.015	0.039	0.037	0.039	0.019	0.063	0.345	**4.31%**
River	0.206	0.214	0.232	0.197	0.185	0.197	0.292	0.147	1.671	**20.88%**
Road	0.088	0.043	0.015	0.039	0.037	0.039	0.019	0.063	0.345	**4.31%**
Slope	0.088	0.214	0.232	0.197	0.062	0.197	0.097	0.088	1.176	**14.70%**
Wetland	0.265	0.300	0.387	0.276	0.555	0.276	0.487	0.440	2.985	**37.32%**
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	8.000	**100.0%**

Figure 4.3 - Criterion Weight Calculation Spreadsheet

4.1.4 System Requirement 4 - Standardise Criteria

Because of the different scales upon which the criteria were measured, the factor raster's needed to be standardised / normalized before combining them. Fuzzy variables possess a natural capability to express and to deal with observation and measurement uncertainties (Klir and Yuan 1995; Munda 1995) in [3] and because of this characteristic, this method was used to standardise each Factor Distance Raster using one of the following fuzzy membership functions:

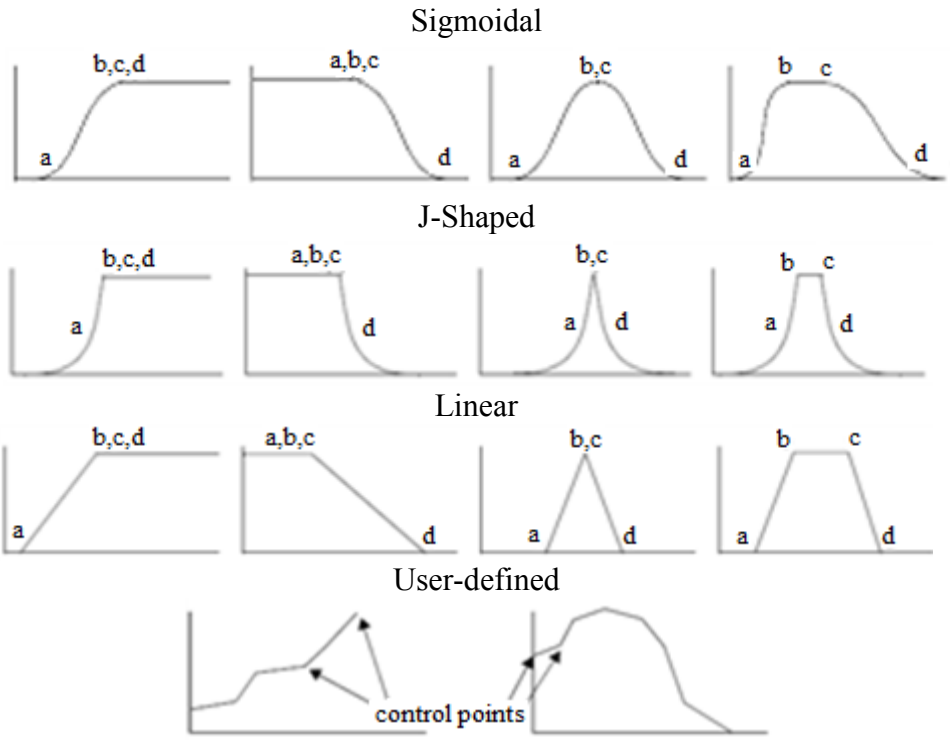


Figure 4.4 - Fuzzy Set Membership Functions [11]

A factor distance raster (Figure 4.5) is a continuous surface of Euclidean distance values from a set of features. Each pixel in the distance raster represents the cumulative Euclidean distance from the feature. The different colours in Figure **4.5** indicate the Euclidean distance from the electrical network factor.

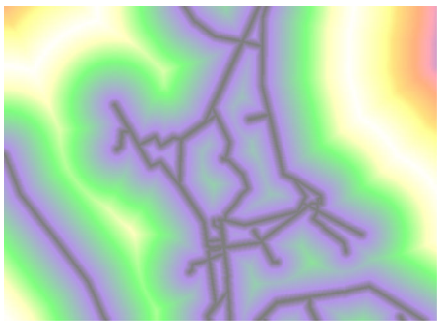


Figure 4.5 - Electrical Network Distance Raster

Each factor distance raster was standardised by selecting fuzzy input parameters that took into account the desired effect. When considering the electrical network a Sigmoidal function with (30,30,30,100) as input was used to standardise the

electrical network distance raster (Figure 4.6). The result was a raster with pixel values within the specified distance(30m) of the electrical network features, shown in green in Figure 4.6, that are more favourable to locating a corridor. Pixels not within this preferred area have equal importance and are shown in red (Figure 4.6).

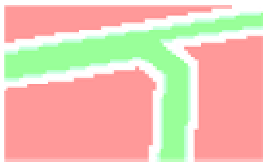
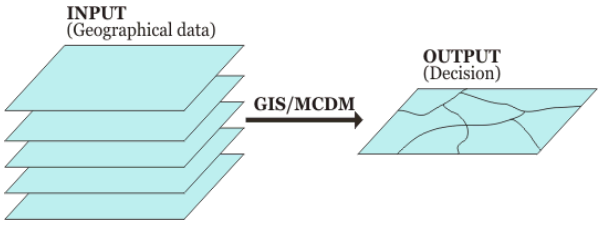


Figure 4.6 - Example Sigmoidal (30,30,30,100)

4.1.5 System Requirement 5 - Evaluate Multiple Criteria Spatially

In spatial multi-criteria evaluation the weighted standardised criterion, have to be spatially combined to form a single spatial layer (Suitability Map). Each pixel's value in this single spatial layer represents the combined resistance to locating a corridor for an OETL at that particular place.



A number of different methods can be used to determine the suitability map (Table 4.4). Of the methods listed in Table 4.4 the Weighted Linear Combination was selected as the method to be used in the prototype SDSS as it is supported by most GIS software including IDRISI Taiga:

Table 4.4 - Methods to determine suitability map

Method
Weighted Linear Combination (WLC)
Multi-attribute value
Multi-attribute utility
Analytic hierarchy process (AHP)
Ideal Point
Concordance
Ordered weighted average

The WLC is based on Equation 4; the factors are combined by applying a weight to each, followed by a summation of the results. The resulting spatial layer is a single combined factor raster.

In cases where constraints needed to be included in the evaluation, the suitability map was determined by the product of the combined factor raster's and the constraint raster's.

$$S = \sum w_i x_i * \prod c_j \quad \text{..... Equation 4}$$

where S = suitability

w_i = weight of factor *i*

x_i = criterion score of factor *i*

$\prod$ = product

c_j = Criterion score of constraint j

Using Equation 4 the following Suitability Map was derived for the criteria and weights in Table **4.3**.

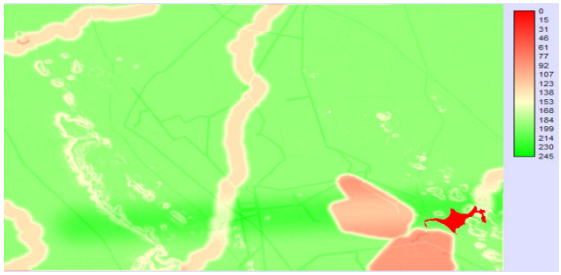


Figure 4.7 – Example of a Suitability Map

The Suitability Map is an indication of a pixel's resistance to locating a corridor at a particular location. A score of 0 (Red) represents a high resistance while a score of 255 (Green) represents the lowest resistance. A colour table (Figure **4.8**) was applied to each Suitability Map to map each pixel value to a particular colour. This ensured that different Suitability Map's could be both programmatically and visually compared as a particular colour consistently represented a certain 'score'.

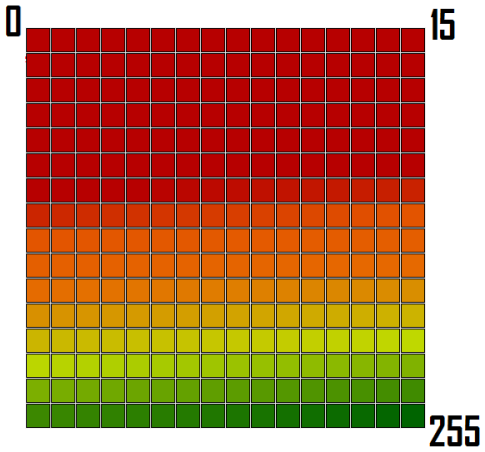


Figure 4.8 - Colour Mapping Table

4.1.6 System Requirement 6 - Determine a Least Cost Route

GIS connectivity functions were used on a friction distance raster to find the path of least resistance from the origin substation to the destination substation. A friction raster (cost of passage surface) was derived by re-sampling the suitability map. During the re-sampling process, it was possible to allocate very high frictional values to pixels that should ideally not form part of the route.

A friction distance raster (accumulated cost surface) is a continuous raster derived from the friction raster and the origin substation. The value of each pixel is a cumulative value of what it will "cost" to travel from the origin to that particular pixel. The friction distance raster incorporates the distance as well as the friction value.

A definition for least cost route could be "The path between two points which has the lowest traversal cost, where cost is a function of the factors being considered" [2]. In the context of this research, the least cost path would be the path from the origin substation to the destination substation that will best satisfy all the criteria taking into account the weighting of the factors.

4.1.7 System Requirement 7 - Preferred Route

One of the initial requirements identified by the SME's was that the length of the selected route should not exceed the shortest distance between the origin and destination substations by more than 20%. The shortest distance specified by the SME's is the straight-line distance between the origin and destination substations. In the model, the route length is constrained by creating a preferred route and then weighting it sufficiently high.

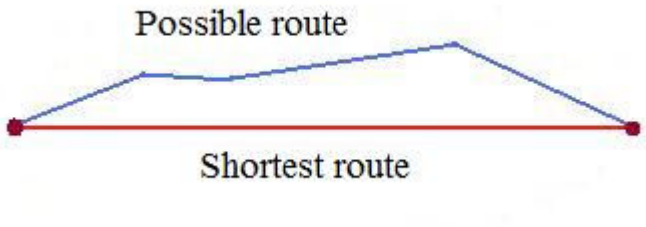


Figure 4.9 – Possible vs. Shortest Route (Preferred Route)

4.1.8 System Requirement 8 – Selection Model

The route selection workflows described in the literature supplied with ArcGIS and IDRISI were reviewed. The process described by Eastman [2] addressed all

the requirements identified by the SME's. IDRISI Taiga was selected as the platform on which to model the corridor selection process suggested by Eastman [2].

The selection model is the primary component of the Corridor Selection SDSS. The model derives a least cost route from an accumulated friction surface. The area around this least cost path represents the area most likely to contain the optimum route. The selection model was modelled as two processes. The first process (Selection Model Process 1) derives from the input data and parameters the standardised spatial layers that are needed by the second process (Selection Model Process 2). Selection Model Process 2 uses the output from Selection Model Process 1 to derive the suitability map and to determine the corridor for the OETL.

A model of each process was built in IDRISI Taiga. IDRISI Taiga is a GIS package that has support for fundamental GIS raster functionality, spatial analysis, spatial multi-criteria analysis and a model-building environment. The model builder made it possible for functions and routines to be combined and executed as a model. The models were easy to execute, could be executed any number of times and the results evaluated, thus making it easy to use in evaluating scenarios.

The model to derive the standardised spatial layers (Selection Model Process 1) made use of the functions listed in **Table 4.5**. Figure **4.10** shows the relationship between these functions.

Table 4.5 – Functions used in Selection Model Process 1

Function	Description [11]
initial	creates a new raster image with the same user-defined value in each cell
shapeidr	converts ESRI Shape files to IDRISI vector files and IDRISI vector files to ESRI Shape files
lineras	converts vector files to raster images and raster images to vector files

Function	Description [11]
distance	measures the Euclidean, *as the crow flies,* distance between each cell and the nearest of a set of target features
fuzzy	evaluates the possibility that each pixel belongs to a fuzzy set by evaluating any of a series of fuzzy set membership functions
surface	calculates slope, aspect and shaded relief images from a continuous surface image, such as a digital elevation model
polyras	converts vector files to raster images and raster images to vector files. Point, line, and polygon object types are supported
reclass	classifies or reclassifies the pixel values stored in images, the feature ID values of vector files or the second column values of attribute values files into new integer categories

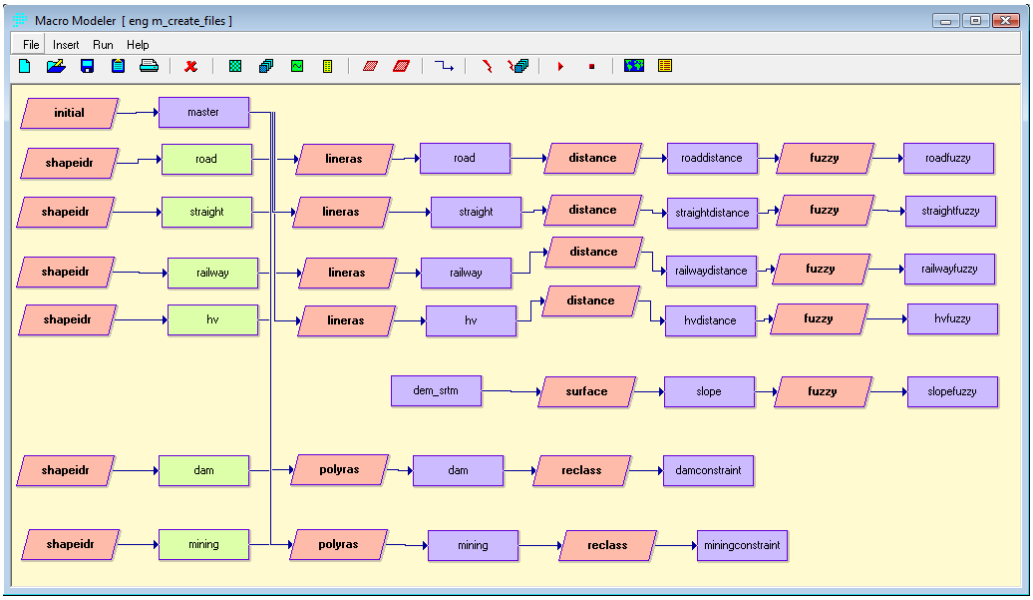


Figure 4.10 – Selection Model: Process 1 Flow Diagram

The Selection Model Process 2 was modelled separately from Selection Model Process 1 as this part of the model was executed more often than Selection Model Process 1.

Selection Model Process 2 made use of the functions listed in **Table 4.6**. Figure **4.11** shows the relationship between the functions used in Selection Model Process 2.

Table 4.6 – Functions used in Selection Model Process 2

Function	Description [11]
mce	is a decision support tool for Multi-Criteria Evaluation. A decision is a choice between alternatives (such as alternative actions, land allocations, etc.). The basis for a decision is known as a criterion. In a Multi-Criteria Evaluation, an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective
assign	creates new images or vector files by linking the geography of features defined in the input file with attributes defined in an attribute values file
cost	generates a distance/proximity surface (also referred to as a cost surface) where distance is measured as the least cost (in terms of effort, expense, etc.) in moving over a friction surface
pointras	converts vector files to raster images and raster images to vector files. Point, line, and polygon object types are supported
pathway	determines the least cost route between one or more targets and one or more lower terminal cells on an accumulated surface such as a cost or a distance surface
polyvec	converts raster images to vector files. Point, line, and polygon object types are supported

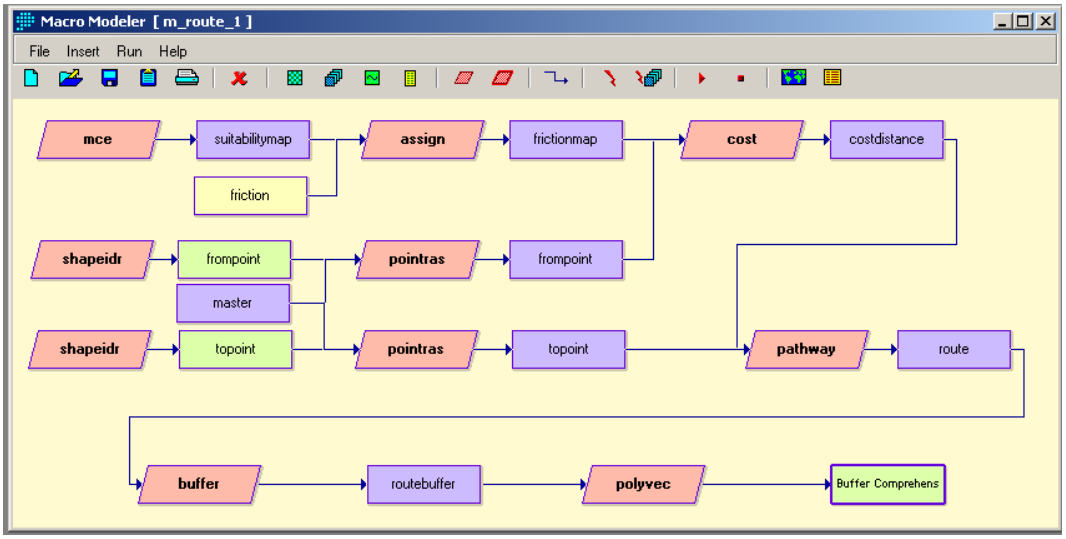


Figure 4.11 – Selection Model: Process 2 Flow Diagram

Figure **4.12** shows the overall operation of the model in a flow diagram. The process begins with the selection of the criteria that will be used. The criteria are represented as spatial layers within the model. A decision is made as to whether each criterion will be treated as a constraint or as a factor. A constraint raster is derived for each constraint and a distance raster for each factor. The distance raster is normalized using a fuzzy set membership function. The normalized factors are ranked using a pair-wise comparison and a weight determined for each one of the factors. A suitability map is then derived using the weighted linear combination function to combine the constraint and normalized factor raster maps. The suitability map is converted to a friction raster (cost of passage surface). A friction distance raster (accumulated cost surface) originating at the origin substation is derived from the friction raster. This accumulated cost surface, a spreading function and the position of the destination substation are used to derive a least cost path. The least cost path is then buffered to depict the corridor.

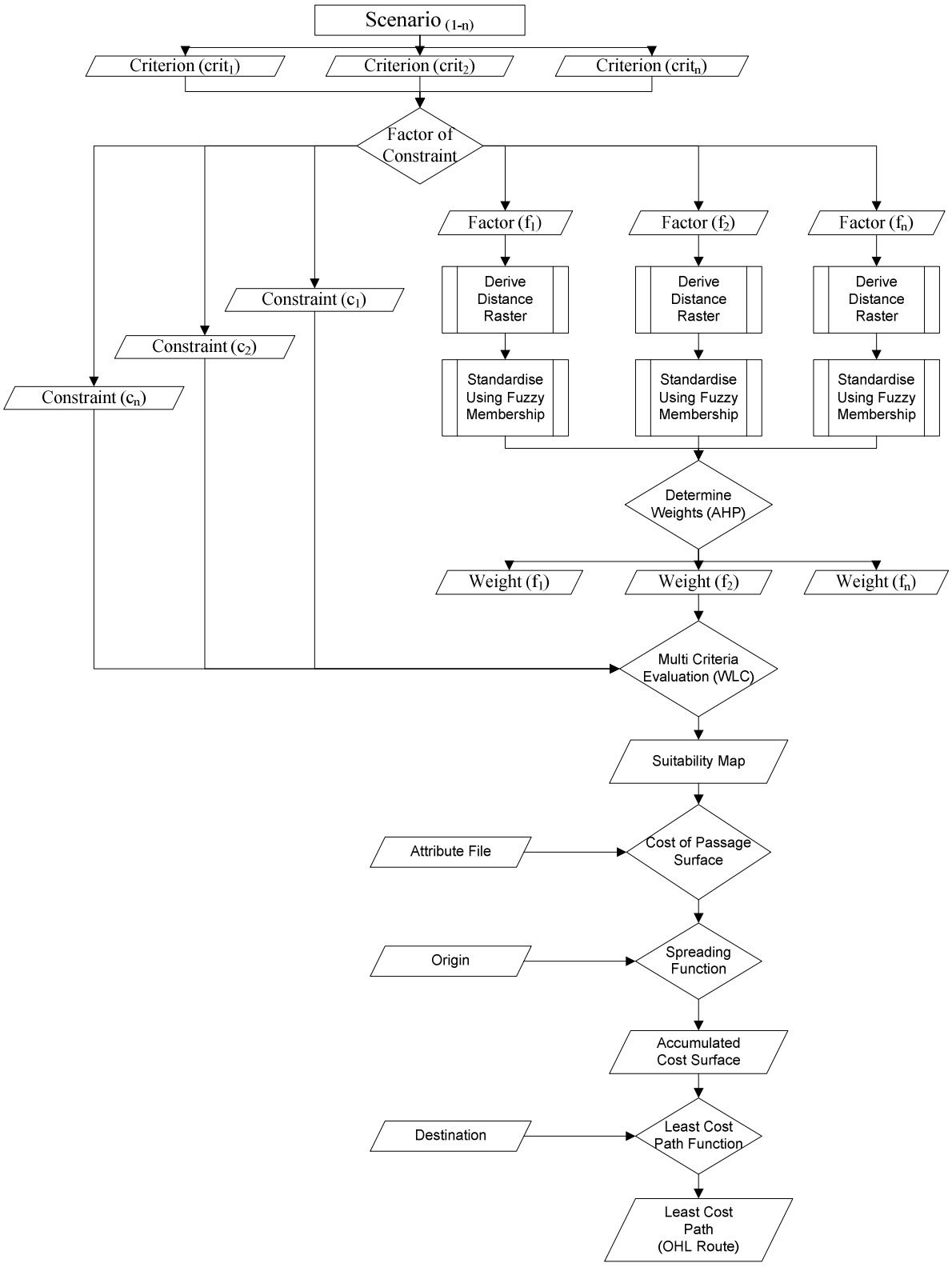


Figure 4.12 - Corridor Selection Model: Flow Diagram

4.1.9 System Requirement 9 - 3D Visualisation

An important aspect in finding a route that is acceptable to all stakeholders is convincing them that all the requirements have been considered equally. Visualizing the results or the impact of changes in criterion and criterion weights is an important part of this process. A projector mounted above a physical 3D model was used to project the prototype SDSS's spatial layers onto the model (Figure **4**.**13**). Different layers and or combinations of layers could be projected onto the model to display different themes. The ease with which this could be done when compared with other methods such as reviewing printouts meant that many more alternatives could be considered and evaluated in less time. Changes in input criteria could be processed and immediately be viewed in combination with other layers.

Physical 3D models have the benefit that people can gather around them, touch and view them from any angle thus allowing for a deeper understanding of the information presented. Physical 3D models provide a level of understanding that cannot be found in any computer model, ordinary topographic model or flat map [14].



Figure 4.13 - Projector Setup and Sample Overlays

Figure **4**.**14** below shows a physical 3D model that was derived from the 90m Shuttle Radar Topography Mission (SRTM) DEM and printed on a ZPrinter 450.



Figure 4.14 - Example of 3D Printed Model

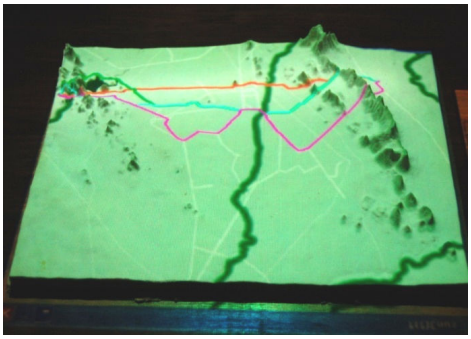


Figure 4.15 - Example of Model Output Overlaid on 3D Printed Model

The advantages of physical 3D models over flat maps and virtual computer models are many [14]. When looking at an actual physical model the information is immediately available, most people "get it" right away- scale, distance, terrain, points of view, sight lines, etc. without knowing how to read a topographical map or grading plan [14].

A disadvantage of the 3D physical model is that the “view scale” is determined at the time that the model is made and can therefore not be adjusted.

The spatial layers could also be presented to the stakeholders in 3D simulation software, making it possible to perform a “fly through” along predetermined paths or dynamically on the fly. This technology allowed for the virtual visualization of a proposed OETL.

A disadvantage of this method is that when zooming in on a particular area one looses perspective in relation to the entire area. An advantage of this method is that the view scale is not fixed so that by zooming in or out it is possible to easily observe any part of the 3D model at literally any scale.

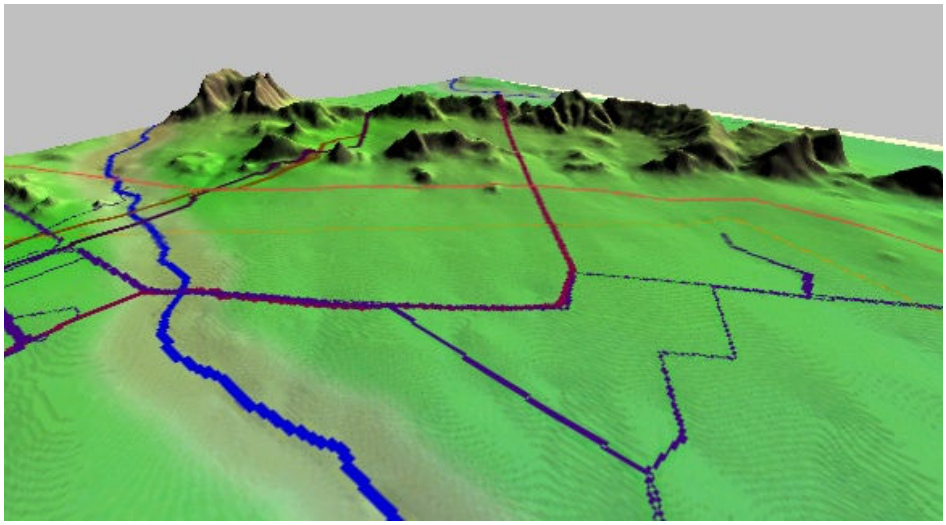


Figure 4.16 - 3D Computer Simulation

4.2 Prototype SDSS

Conceptually a SDSS can be thought of as a system that provides a set of flexible capabilities [15]. There are several components that when combined makeup the core of a SDSS. In this paragraph and its sub paragraphs the design considerations for integrating the concepts, methods and approaches (discussed in paragraph 4.1), a GIS and a corridor selection model into a SDSS are presented. The six major components of the prototype SDSS are:

- GIS Application
- Geographical database
- User interface
- System interface
- Corridor selection model
- Visualizing the results

4.2.1 GIS Application

Modern GIS's are capable of storing, manipulating and analysing geographically referenced data to create output in the form of maps or tabular reports. Most of the GIS's currently available cannot be used to solve structured problems directly (Densham and Goodchild) in [15]. The prototype SDSS developed combined spreadsheets, IDRISI Taiga (a raster GIS) and physical 3D models. IDRISI Taiga has a powerful model builder environment that made it possible to assemble the corridor selection model.

4.2.2 Geographical Database

The geographical database was used for storing and maintaining the spatial data. The input criteria were firstly stored in the geographical database in vector format as ESRI shape files. The spatial data for each criterion was projected to a similar coordinate system and converted to the raster data format and saved in the geographical database. Each raster was stored at the same resolution making it easier for the analysis tools to process and compare the data. A different database was created for each scenario.

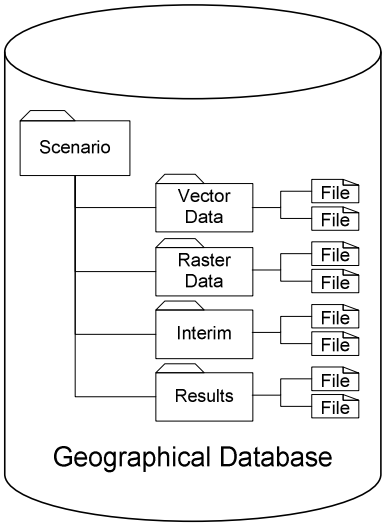


Figure 4.17 – Geographical Database Structure

4.2.3 User interface

The user interface made use of the dialog boxes within IDRISI Taiga to provide the user with access to the data in the geographical database, the spatial analysis functions, the model builder and the spatial layers generated.

4.2.4 System interface

The prototype SDSS used the system interface built into ERISI Taiga. The system interface managed the transferring of the data between the geographical database and the spatial analysis and decision making functions. The routines responsible for this were invoked automatically when the models were executed within the IDRISI modelling environment.

4.2.5 Corridor Selection Model

The Selection Model was a key component of the SDSS in that it consisted of the tools that were used to convert the input data (criteria) to a decision. The Selection Model was assembled in the IDRISI Taiga model builder and saved as a file in the database through the user interface. The decision, represented by the selected corridor was determined when the model was executed. The data required by the model was loaded into the functions by the system interface. The final and interim results (spatial layers) were saved in the geographical database through the system interface.

4.2.6 Visualisation of the Results

The sixth and final component of the prototype SDSS was the visualisation of the results that were derived by the selection model. The results were saved in the geographical database in the form of spatial layers. The spatial layers were combined to form maps using the user and system interfaces.

4.3 Summary

In this chapter the user and system requirements were explained as well are the solutions that were selected to address these requirements. A prototype SDSS was

introduced and the Selection Model described. In the next chapter, chapter 5, the effectiveness of the Selection Model is evaluated by using it to determine a corridor for three different scenarios.

5 Evaluating the Selection Process/Model

To evaluate the effectiveness of the corridor selection process the model was used to determine a corridor for a hypothetical OETL using criteria for three different scenarios. In the first scenario criteria were selected and weighted with a bias towards engineering, the second scenario was biased towards environmental considerations and the third scenario evaluated a comprehensive set of criteria including criteria from the first two scenarios. The effectiveness of the selection process was evaluated by comparing each of the three routes to the stated objective for each scenario. More specifically, did the model select a corridor that avoided features that should have been avoided and approach features that should have been approached?

5.1 Study Area

A number of new mines and extensions to existing mines are currently in the planning phase. Knowledge of these developments is sensitive and it is therefore not easily divulged. An area (Figure 5.1) that can be considered typical of such expansion projects was selected and a start and end point for a hypothetical overhead transmission line identified.

The study area consists of a mountain range in the southwest, a dam and some hills in the southeast. Most of the mining related activity takes place on the level area between the mountain range and the dam. The electrical network, road and rail infrastructure that supports the mining and residential areas cross the study area in various directions. The wetland that is located to the north west of the dam and to the east of the major mining activity and the river that flows from south to north through the study area are the most environmentally sensitive areas within the study area.

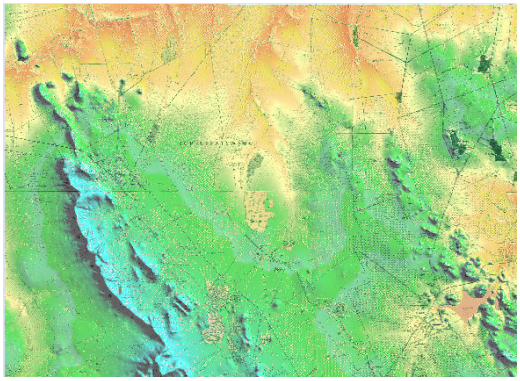


Figure 5.1- Map of the Study Area

5.2 Scenarios

The criteria for each of the three scenarios were evaluated separately by consulting the SME's and then executing the model using the criteria and input parameters specified by the SME's. A table similar to Table 5.1 was compiled for each scenario. In each scenario's discussion paragraphs the information contained in the table is referenced by means of a spreadsheet style referencing system. Columns are numbered A,B,C..., rows 1,2,3... and individual cells A1, A2.... (column row). For example in **Table 5.1** the weight derived for factor 4 is referenced as "3.47% {L7}". A range of cells is referenced as A3:C5 (column row: column row).

Each table consists of four areas shaded green, grey, yellow and blue representing the Fuzzy Membership Input Parameters, Criteria considered, Pair-wise Comparison and the Weights derived respectively.

Table 5.1 - Scenario Parameters: Generic Layout

	A	B	C	D	E	F	G	H	I	J	K	L
1			Criteria	Pairwise Comparison								
2	Fuzzy Membership Input Parameters											
3	Function	Parameters	Factors	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Weights
4	Sigmoidal	P1 P2 P3 P4	Factor 1	1								27.07%
5	Sigmoidal	P1 P2 P3 P5	Factor 2	1/7	1							1.94%
6	Sigmoidal	P1 P2 P3 P6	Factor 3	1/8	4	1						3.47%
7	***Sigmoidal***	***P1 P2 P3 P7***	***Factor 4***	***1/8***	***4***	***1***	***1***					***3.47%***
8	Sigmoidal	P1 P2 P3 P8	Factor 5	1/8	4	1	1	1				3.36%
9	Sigmoidal	P1 P2 P3 P9	Factor 6	3	9	9	9	9	1			39.24%
10	Sigmoidal	P1 P2 P3 P10	Factor 7	1/3	5	5	5	5	1/4	1		14.46%
11	Sigmoidal	P1 P2 P3 P11	Factor 8	1/9	4	3	3	5	1/9	1/5	1	6.99%
12												100.00%
13											Consistency ratio:	0.10
14											Consistency is:	Acceptable
15												
16			Constraints									
17			Constraint 1									

5.2.1 Engineering Scenario

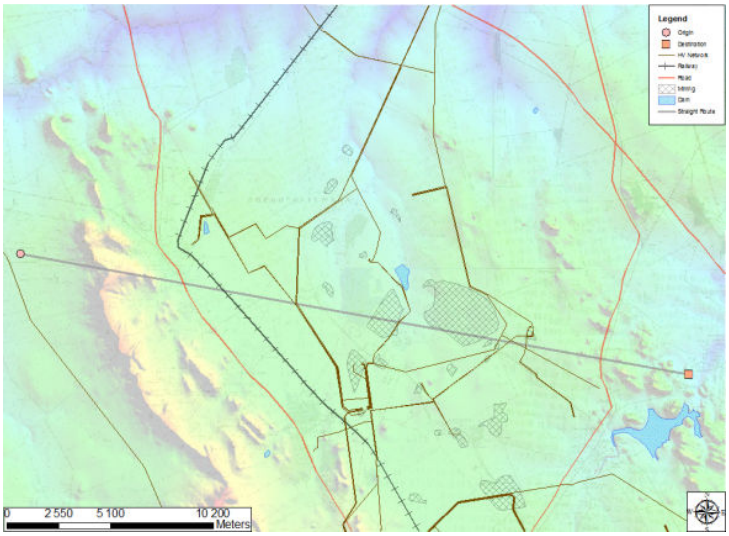


Figure 5.2 - Engineering Scenario: Map of Input Criteria

Table 5.2 - Scenario Parameters: Engineering Scenario

	A	B	C	D	E	F	G	H	I
1			Criteria	Pairwise Comparison					
2	Input Parameters								
3	Function	Parameters	Factors	straight	hv	railway	road	slope	Weights
4	Sigmoidal	0 0 0 3000	straight	1					41.85%
5	Sigmoidal	30 30 30 100	hv	4	1				15.99%
6	Sigmoidal	50 50 50 100	railway	1/3	1/4	1			6.18%
7	Sigmoidal	20 20 20 50	road	3	1/3	3	1		9.73%
8	Sigmoidal	0 0 0 12	slope	4	3	7	6	1	26.25%
9									100.00%
10				Consistency ratio:					0.02
11				Consistency is:					Acceptable
12									
13			Constraints						
14			Dam						
15			Mining						

Pairwise Comparison Legend		
	Value	Relative Preference
Less Important	1/9	extremely
	1/7	very strongly
	1/5	strongly
	1/3	moderately
	1	equally
More Important	3	moderately
	5	strongly
	7	very strongly
	9	extremely

In the engineering scenario the model was used to evaluate the seven criteria {Column C} listed in Table 5.2. These criteria were selected by the SME's and classified as either a factor {C4:C8} or a constraint {C14:C15}. Of the seven criteria, dams and areas zoned for mining related activities were considered 'no go areas' and therefore classified as constraints. The five factors were prioritised using the pair-wise comparison (AHP) {C3:H8} method.

The dams were classified as a constraint due to the cost and complexity of erecting towers in or close to the dam. Performing maintenance and repairing faults on a power line crossing a dam would also be more complex than on a power line not crossing a dam.

The areas zoned for mining activity could in future be used to establish dumps, slime dams, be undermined or surface mined. Each of these land uses would impact the stability and or performance of an OETL and therefore the OETL would have to be relocated. The potential risk of relocation and the possibility of structural damage that could occur as a result of the activities associated with mining persuaded the SME's to classify areas zoned for mining as a constraint.

The ideal route for an OETL from an engineering perspective would be the shortest route from the origin substation to the destination substation. The straight {Row 4} factor was used as a proxy factor for the shortest route. This straight route was considered ideal as it would result in a route with the lowest technical losses and most likely be the cheapest to construct and maintain. A weight of 42% {I4} was determined for the "straight" factor making it the most important of the factors considered in this scenario. The fuzzy membership parameters {B4) used to standardise the straight factor were selected to make it preferable to route the OETL within 3000m of the 'straight route'.

To erect and maintain an OETL along or over steep areas is more expensive than along or over less steep areas. The increase in cost can be attributed to more expensive construction techniques, accessibility and design parameters. A weight of 26% was determined for the slope {Row 8} factor and slopes below 12 degrees were considered preferable.

OETL's are routinely inspected and maintained, it was therefore considered preferable to (when possible) route any new OETL along the same route as existing OETL's. A weight of 16% was determined for the "hv" (HV Network) {Row 5} factor. The parameters used for the fuzzy membership function prioritized the area between 30 and a 100m from existing OETL's.

The other factors considered in the engineering scenario were the road {Row 7} and railway {Row 6} factors. Both these factors are linear features and give some indication of a suitable route for an OETL, as similar factors would be considered when selecting a route for these features. Roads were considered 'moderately more' important than railway lines as they could be used to gain access to the OETL for maintenance or repair purposes. Weights of 10% and 6% were determined for the road and railway factors respectively.

5.2.2 Environmental Scenario

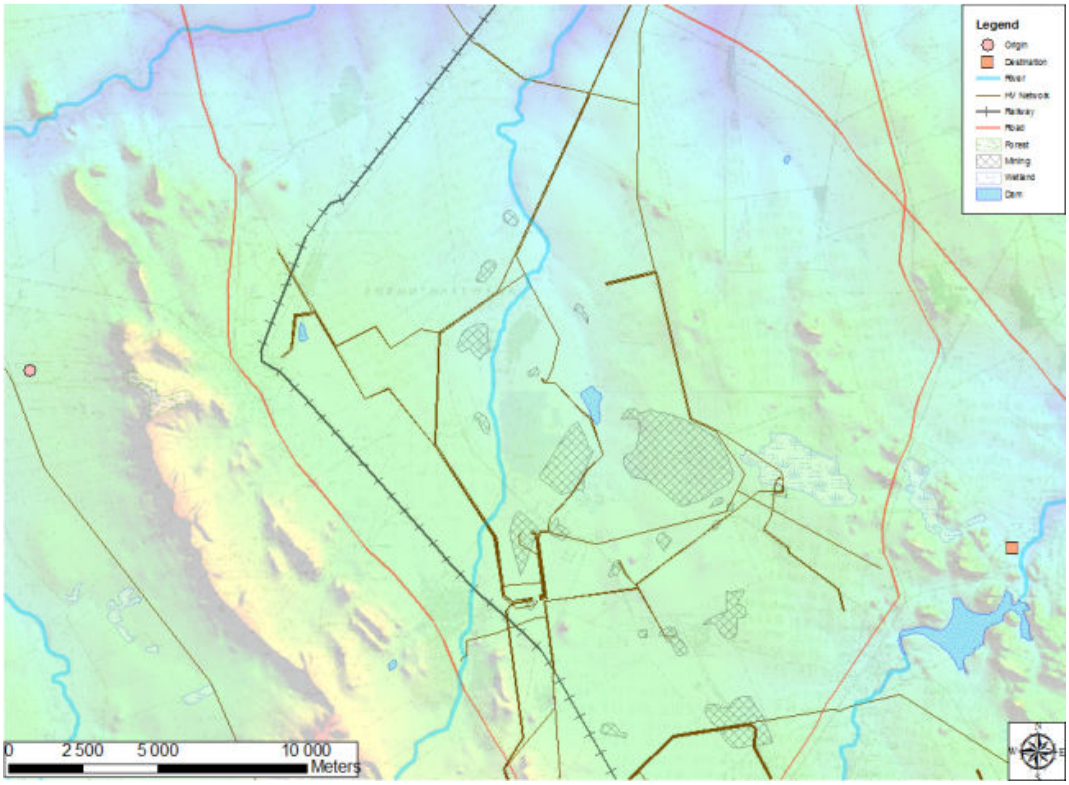


Figure 5.3 - Environmental Scenario: Map of Input Criteria

Table 5.3 - Scenario Parameters: Environmental Scenario

	A	B	C	D	E	F	G	H	I	J	K	L
1			Criteria	Pairwise Comparison								
2	Fuzzy Membership Input Parameters											
3	Function	Parameters	Factors	river	preferred	hv	railway	road	wetland	forest	mining	Weights
4	Sigmoidal	300 2000 2000 2000	river	1								27.07%
5	Sigmoidal	0 0 0 1500	preferred	1/7	1							1.94%
6	Sigmoidal	30 30 30 500	hv	1/8	4	1						3.47%
7	Sigmoidal	50 50 50 500	railway	1/8	4	1	1					3.47%
8	Sigmoidal	20 20 20 500	road	1/8	4	1	1	1				3.36%
9	Sigmoidal	300 2000 2000 2000	wetland	3	9	9	9	9	1			39.24%
10	Sigmoidal	150 1000 1000 1000	forest	1/3	5	5	5	5	1/4	1		14.46%
11	Sigmoidal	0 0 0 50	mining	1/9	4	3	3	5	1/9	1/5	1	6.99%
12												100.00%
13											Consistency ratio:	0.10
14											Consistency is:	Acceptable
15			Constraints									
16			Dam									

Pairwise Comparison Legend		
	Value	Relative Preference
Less Important	1/9	extremely
	1/7	very strongly
	1/5	strongly
	1/3	moderately
	1	equally
More Important	3	moderately
	5	strongly
	7	very strongly
	9	extremely

In the environmental scenario, the 9 criteria {Column C} in Table 5.3 were evaluated with a bias towards limiting the impact that an OETL would have on the environment. The dam {Row 16} criterion was considered an environmentally

sensitive area that should not be disturbed by either construction or maintenance activities. The dam criterion was classified as a constraint with the remaining criteria classified as factors, The factors {Row 4 : Row 11} were prioritised using the pair-wise comparison method {Column D : Column K}

It could be argued that land being used for mining has already been environmentally compromised and therefore the areas zoned for mining were considered suitable for locating an OETL. A weight of 7% was determined for the "mining" factor {Row 11}. The parameters used for the fuzzy membership function prioritized the area zoned for mining plus the area within 50m of areas zoned for mining.

Rivers are an important part of ecosystems as they provide a habitat for wildlife and a great place for people to enjoy walks, fishing and other water sports. Rivers provide water for [16]:

- us to drink
- crops and farm animals
- industries that produce food and electricity etc.

A weight of 27% was determined for the "river" factor {Row 4}. The parameters used for the fuzzy membership function prioritized the area within 2000m of a river thereby ensuring that the area within 2000m of a river is avoided.

Wetlands are unique and vital to the health of other biomes, wildlife and humans [16].Wetlands cannot be thought of as an isolated and independent habitat as they directly improve other ecosystems. "*Due to its many cleansing benefits, wetlands have been compared to kidneys. The analogy is good one. Wetlands and kidneys both help control water flow and cleanse the system"* [16].

Wetlands fulfil an important role in an Ecosystem. They prevent flooding by holding water much like a sponge. In doing so wetlands help maintain normal water levels and in the process filter and purify the surface water. Wetlands accept

water during storms or whenever water levels are high and when water levels are low they slowly release the water and in the process they counter the erosive forces of moving water along lakes and rivers [16].

Wetlands also release vegetative matter into rivers which help to feed the fish in the rivers [16]. *Wetlands help to counter balance the human effect on rivers by rejuvenating them and surrounding ecosystems* [16]. Many animals that live in other habitats also use wetlands for migration or reproduction.

A weight of 39% was determined for the “wetland” factor {Row 9}. The parameters used for the fuzzy membership function prioritised the area within 2000m of the wetland thereby ensuring that the area covered by the wetland as well as the area within 2000m of the wetland is avoided.

No matter where on the planet we live, forests are essential to our quality of life [16]. The forests of the world temper our climate; filter the air and water, acting much like a global air conditioning unit [16]. Forests are often called 'carbon sinks' because they convert carbon dioxide to oxygen. Carbon is a greenhouse gas, and when highly concentrated in the atmosphere, contributes to climate change.

Forests are not simply wonderful places to spend time and ponder the natural world. Forests are much more than their often-majestic trees as they provide habitat for an incredible diversity of life, including flowering plants, shrubs, mosses, lichens and fungi. This biodiversity supports a wide range of animals from large mammals to migratory birds, rodents, and insects. Forests help prevent erosion by retaining vital topsoil that's essential to the entire ecosystem. Forests regulate stream flows to prevent flooding, and shade these streams, cooling the water and providing a stable habitat for fish [16].

A weight of 14% was determined for the “forest” factor {Row 10}. The parameters used for the fuzzy membership function prioritized the area covered by

the forest plus the area within 1000m of the forest thereby ensuring that the forest plus the area within 1000m of the forest would be avoided.

The preferred route factor {Row 5} was used to avoid or give preference to specific places between the origin and destination substations of the OETL. The preferred route could also be used to limit the length of the route determined by the model. A weight of 2% was determined for the "preferred" factor. The parameters used for the fuzzy membership function prioritized the area within 1500m of the preferred route.

Electrical HV networks, roads and railway lines are manmade features {Row 6:Row 8} that are already having an impacted on the environment. The impact that a new OETL will have on the environment could therefore be reduced by aligning the new OETL with these existing features. A weight of 3% was determined for each of these three features. The area within 30-500m, 20-500m and 50-500m was prioritized by means of a Sigmoidal fuzzy membership function.

5.2.3 Comprehensive Scenario

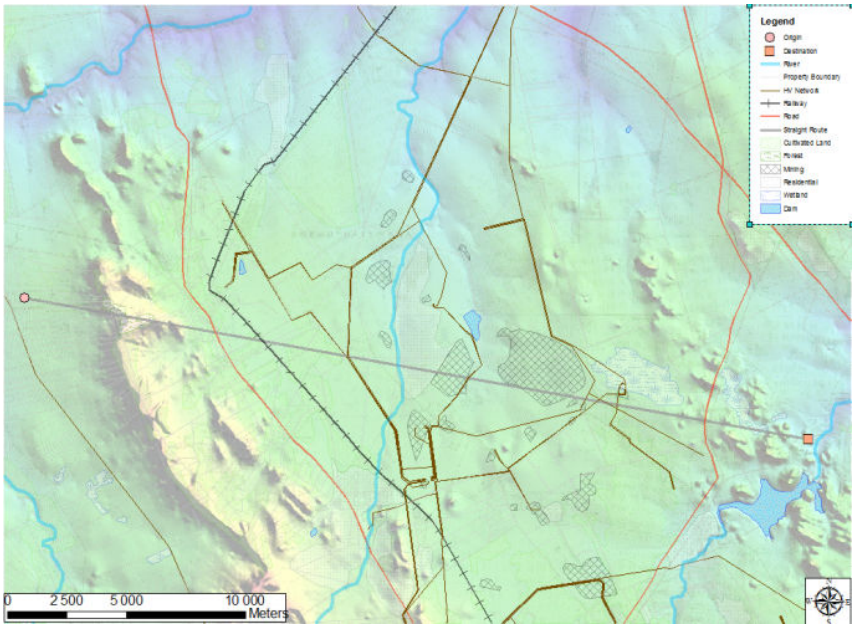


Figure 5.4 - Comprehensive Scenario: Map of Input Criteria

Table 5.4 - Scenario Parameters: Comprehensive Scenario

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1			Criteria	Pairwise Comparison											
2	Parameters														
3	Function	Parameters	Factors	straight	boundary	hv	railway	river	road	cultivated	forest	residential	wetland	slope	Weights
4	Sigmoidal	0 0 0 1500	straight	1											2.90%
5	Sigmoidal	5 5 5 20	boundary	1/5	1										1.32%
6	Sigmoidal	30 30 30 100	hv	4	6	1									5.00%
7	Sigmoidal	50 50 50 100	railway	1/3	2	1/4	1								1.68%
8	Sigmoidal	300 1000 1000 1000	river	6	8	5	8	1							23.37%
9	Sigmoidal	60 60 60 100	road	3	3	1/3	3	1/5	1						3.20%
10	Sigmoidal	50 500 500 500	cultivated	2	5	3	4	1/6	4	1					5.85%
11	Sigmoidal	100 500 500 500	forest	2	6	2	4	1/5	4	1	1				6.33%
12	Sigmoidal	300 1000 1000 1000	residential	5	6	4	5	1/6	5	5	2	1			10.59%
13	Sigmoidal	300 1000 1000 1000	wetland	7	9	6	8	2	5	6	4	5	1		25.66%
14	Sigmoidal	0 0 0 12	slope	4	7	3	7	1/3	6	4	2	4	1/3	1	14.10%
15															100.00%
16													Consistency ratio:		0.1
17													Consistency is:		acceptable
18															
19			Constraints												
20			Dam												
21			Mining												

Pairwise Comparison Legend		
	Value	Relative Preference
Less Important	1/9	extremely
	1/7	very strongly
	1/5	strongly
	1/3	moderately
	1	equally
More Important	3	moderately
	5	strongly
	7	very strongly
	9	extremely

In the Comprehensive Scenario all, the criteria {Column C} from the engineering and environmental scenarios were considered as well as these additional criteria:

- Land Parcel Boundaries
- Cultivated Land
- Residential Areas

In this scenario as in both the engineering and environmental scenario the ‘dam’ criteria {Row20} was considered a constraint. The possibility of relocating an OETL due to mining activity, the cost involved in relocating and the negative impact that this would have on the environment resulted in the mining criteria {Row 21} being classified as a constraint in this scenario.

Wetlands {Row 13}, rivers {Row 8} and forests {Row 11} were considered the most environmentally sensitive of the criteria, each of these factors also pose challengers from a construction and maintenance perspective. Fuzzy membership input parameters of (300 1000 1000 1000), (300 1000 1000 1000) and (100 500 500 500) were used for these factors to ensure that these features would be avoided. Weights of 26%, 23% and 6% were calculated for each factor respectively.

It was considered beneficial that the derived corridor should approach the existing three linear man-made features hv (HV Network) {Row 6}, railway {Row 7} and road {Row 9} rather than avoid them. Fuzzy membership input parameters where selected that would ensure a lower resistance to locating the route close to these features. Weights of 5%, 2% and 3% were determined for hv (HV network), railway and roads respectively.

In most cases, the shortest route should result in the lowest construction and operational cost as well as have the least impact on the environment as less of the environment is affected. A weight of 3% was determined for the straight factor {Row 4}.

Should humans come into contact with electrical power lines it could be fatal. Activities normally associated with human settlements impact on the performance of power lines and therefore residential areas are normally avoided when selecting a route for an OETL's. A weight of 11% was determined for the residential factor {Row 12}.

Part of the process of establishing an OETL route is obtaining approval from the landowner. By aligning the route with the property boundary and avoiding cultivated land, it should be easier to obtain the landowners approval. A further consideration was that cultivated lands are often irrigated by means of centre pivots, which should be avoided due to the hazards they pose to OETL's. The boundary factor {Row 5} with fuzzy input parameters (5 5 5 20) was used to align the route with the boundary, a weight of 1% was determined for this factor. Cultivated land {Row 10} should be avoided and therefore (50 500 500 500) was used as fuzzy membership input parameters. A weight of 6% was determined for the cultivated factor.

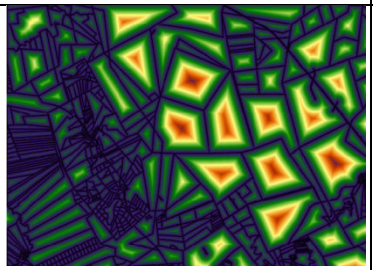
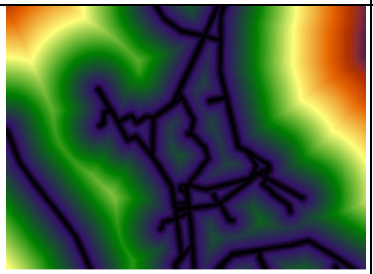
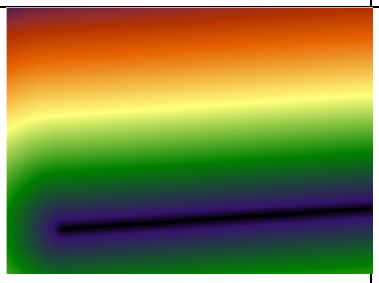
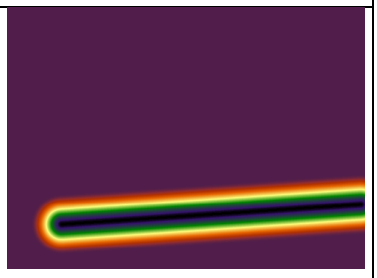
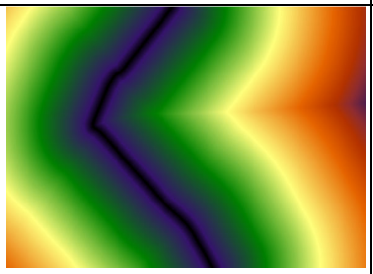
The SME's selected a slope {Row 14} cut-off of 12 degrees which was used to determine the standardised slope map. The slope map was standardised using (0 0

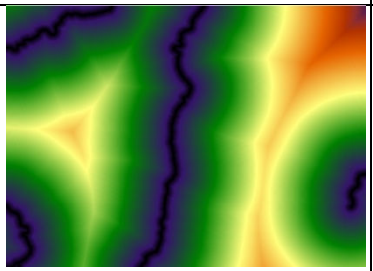
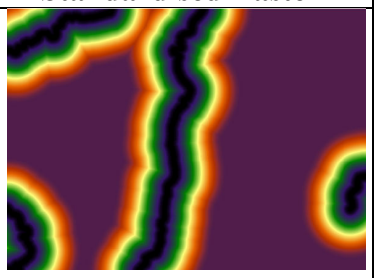
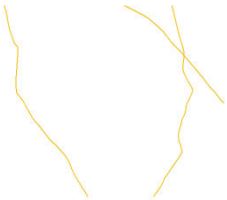
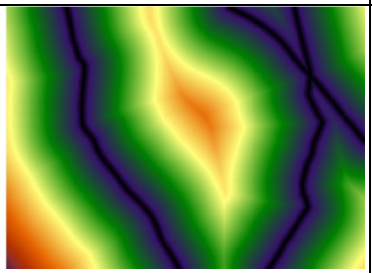
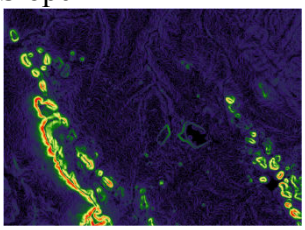
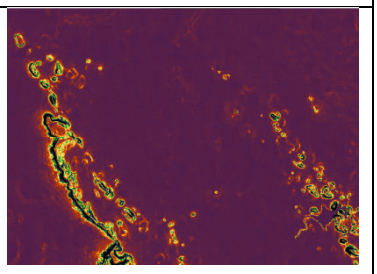
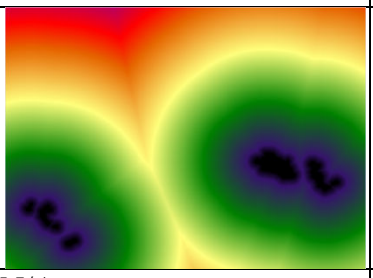
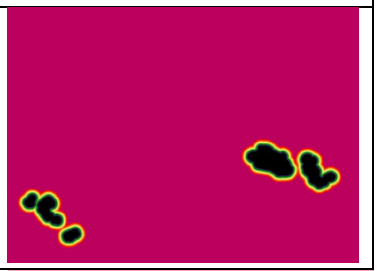
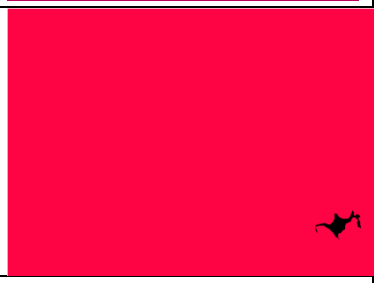
0 12) as input to the fuzzy membership function. A weight of 14% was determined for the slope factor.

5.3 Examples of Input and Evaluated Spatial Data

Table 5.5 below illustrates the input criteria and the output derived during the evaluation of the criteria.

Table 5.5 - Spatial Evaluation of Input and Output Criteria Examples

Criteria	Distance Raster	Standardised Raster
Farm Boundary 		
HV Network 		
Preferred Route 		
Railway 		

Criteria	Distance Raster	Standardised Raster
River 		
Road 		
Slope 	N/A	
Wetland 		
Dam 	N/A	

5.4 Summary

The evaluation of the three scenarios that were selected to evaluate the effectiveness of the Selection Model was described in this chapter. The results of this evaluation are presented in the next chapter, chapter 6.

6 Results and Discussions

6.1 Deriving Standardised Spatial Layers

The data used in this research was typical of the data that would be available for similar studies in other areas. No metadata was available for the data used in this research and therefore the positional accuracy could not be confirmed. The fuzzy membership functions used to standardise the data made it possible to use this data. By standardizing the factors, the factors were comparable; this made it possible to combine them, which in turn made it possible to prioritize specific areas for locating a corridor.

The use of fuzzy membership functions was a key principle of this research. Figure 6.1 below shows that by applying fuzzy membership functions to a factor distance raster it was possible to create a raster with pixel values that gave preference to locating a corridor within a specified distance from a feature. The pixels that were not within this specified distance were all allocated the same value (red pixels in Figure 6.1).



Figure 6.1 - Electrical Network Standardised Raster

The opposite effect to the one described above was obtained by specifying (300, 1000, 1000, 1000) as input to the sigmoidal function. By specifying the inputs in this manner, a result that was ideal for an environmentally sensitive area such as a river was obtained. That is an area with pixel values to avoid was created immediately adjacent to the feature. The pixels outside of this area were assigned values that were more favourable to locating a corridor (Figure 6.2).

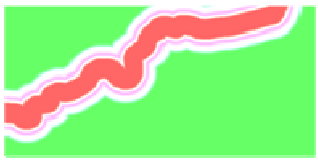


Figure 6.2 - Example Sigmoidal (300,1000,1000,1000)

6.2 Prioritising Criteria

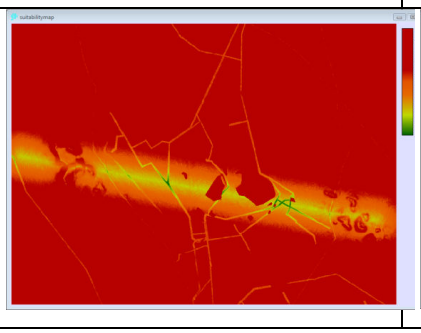
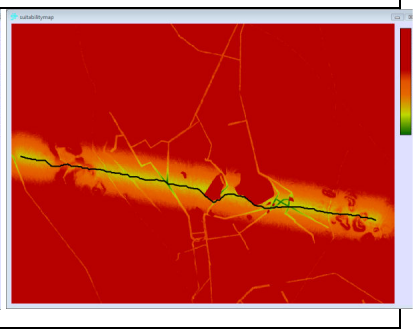
The derivation of weights for each of the criteria used in determining a corridor was essential and an integral part of the process used to determine a corridor for an OETL. The weights for each scenario were generated using the AHP. The sum of the weights should equal 1 and the consistency ratio should be below 10%. The criterion with the largest weight was considered the most important of the factors forming part of the scenario.

6.3 Engineering Scenario

The weights determined for the Engineering Scenario indicated that the most important factor was the distance between the source and destination substations. The ranking of the weights determined by the AHP were consistent with the expectations of the SME's. On the suitability map (**Table 6.1**) the areas more suitable to locating an OETL are indicated by green and yellow. These areas are consistent with the position and weights of the relevant evaluation criteria. The least cost route determined from the suitability map was located within these areas. The route avoided the areas with steeper slopes and only deviated from the

straight feature to align with the hv, road and railway features as well as to find a path around the mining feature that was classified as a constraint.

Table 6.1 - Engineering Scenario Input and Output

Weights		Suitability Map	Derived Route
railway	6%		
road	10%		
hv	16%		
slope	26%		
straight	42%		

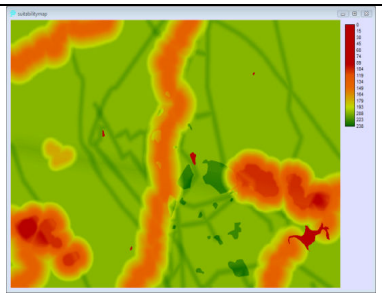
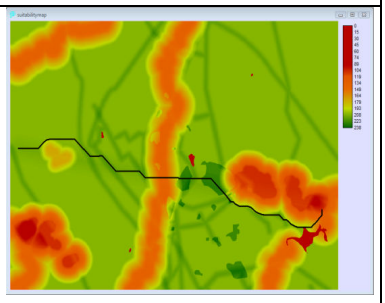
6.4 Environmental Scenario

The weights determined for the environmental scenario indicated that the most important factor was the wetland with a weight of 39% followed by the other environmentally sensitive factors namely the river and forest factors with weights of 27% and 14% respectively. In this scenario, engineering factors and environmental factors were evaluated with a bias towards protecting the environment.

The SME's from all the disciplines accepted the ranking of the weights and were in agreement with the suitability map derived for this scenario. The red and orange areas on the suitability map indicated the areas that should be avoided when selecting a corridor for an OETL. The areas that should be avoided coincided with the factors for which the higher weights were determined. The route derived for this scenario avoided the areas that should have been avoided except where no alternative route was available, such as crossing the river and the section of the route at the destination substation. The route follows the preferred, road, hv and railway features where possible. In this scenario the mining feature was not classified as a constraint, in fact it was considered preferable to route the corridor across the mining feature. The dam feature was classified as a constraint

and is depicted by the red areas on the suitability map. The derived route did cross the mining feature but never crossed any of the dam features.

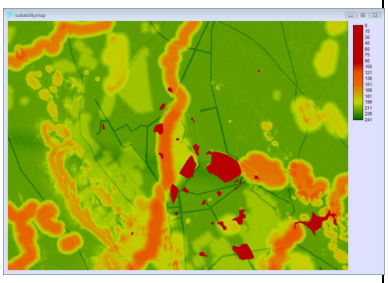
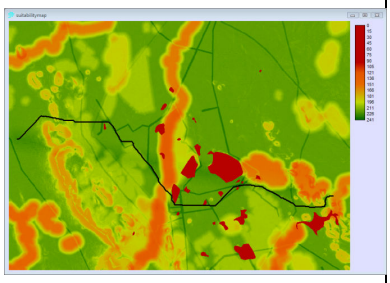
Table 6.2 - Environmental Scenario Input and Output

Weights		Suitability Map	Derived Route
preferred	2%		
road	3%		
hv	3%		
railway	3%		
mining	7%		
forest	14%		
river	27%		
wetland	39%		

6.5 Comprehensive Scenario

The Comprehensive Scenario considered factors from more than the engineering and environmental disciplines. In this scenario the wetland and river where ranked highest of the criteria with weights of 26 and 23% respectively. This was in line with the expectations of the SME's as both these features were considered features that should be avoided albeit for different reasons. The wetland and river pose construction and maintenance challenges for the engineers while for the environmentalists they are areas that should not be disturbed by construction and maintenance activities. The ranking of the features were accepted by the SME's. The SME's agreed that the suitability map accurately represented the features and their weights. When compared with the suitability maps of the other scenarios the suitability map for the comprehensive scenario is more restrictive as to possible corridors for an OETL. This is demonstrated by the amount of red or orange pixels in the suitability map. The derived route avoided all the constraints (dams and mining areas) and followed the areas that had been determined to be more suitable for locating an OETL. The derived route was accepted by all the SME's. Although the engineering representatives would have preferred a shorter more direct route, they acknowledged that the derived route was in line with the weighting of the factors.

Table 6.3 - Comprehensive Scenario Input and Output

Weights		Suitability Map	Derived Route
boundary	1%		
railway	2%		
straight	3%		
road	3%		
hv	5%		
cultivated	6%		
forest	6%		
residential	11%		
slope	14%		
river	23%		
wetland	26%		

6.6 Comparing the Corridors

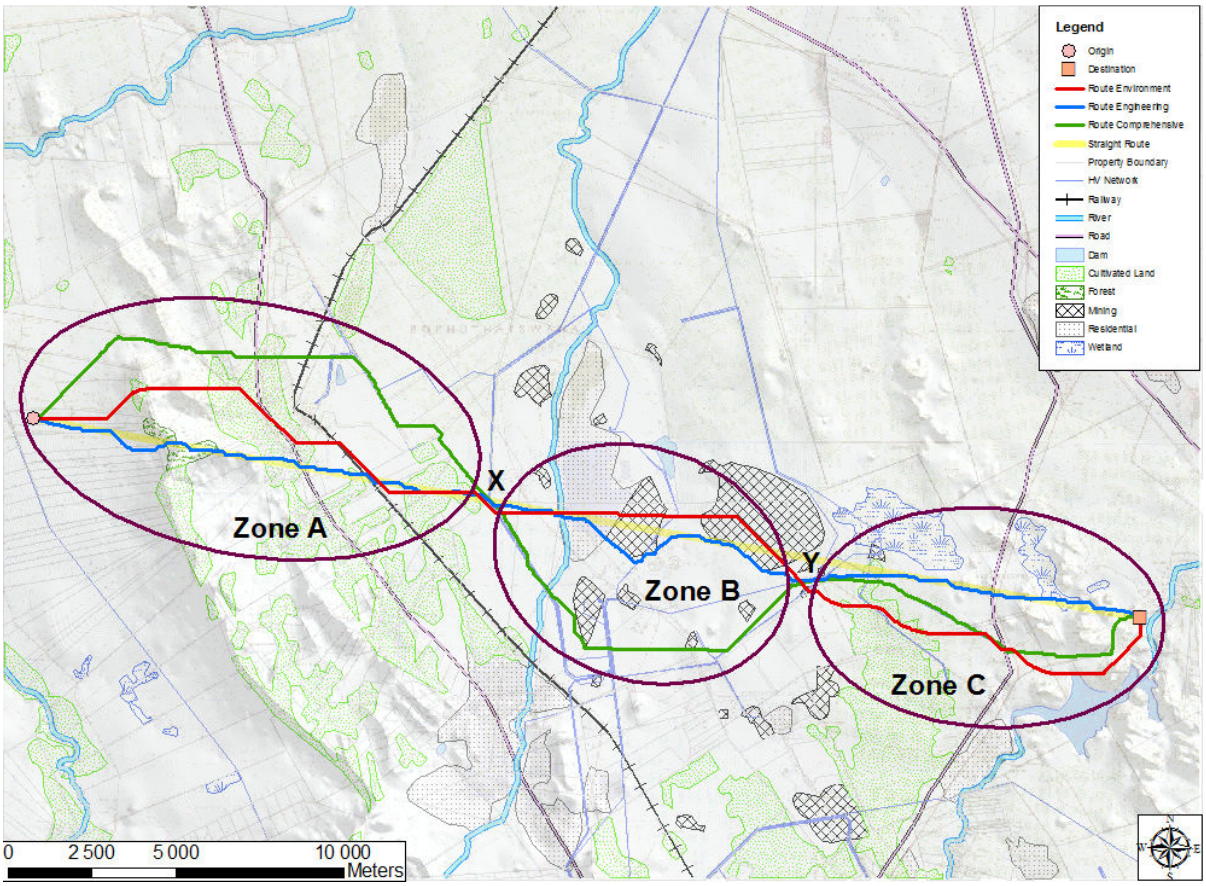


Figure 6.3 - Corridors: 3 Scenarios Combined

Except for at the origin and destination substations the three scenarios yielded comparable corridors at X and Y (Figure **6.3**) establishing zones A, B and C where the corridors differ significantly from each other.

In zone A the corridors follow different paths mostly due to the influence of the slope criterion. In the engineering scenario, slope was weighted high but not as high as the straight criterion and therefore the corridor tended to follow the straight feature. In the environmental scenario, slope was not evaluated but the forest situated on the direct path between the origin and destination substations resulted in the corridor deviating to the north before returning via the road and railway features to coincide with the engineering corridor towards the end of Zone A. In the comprehensive scenario, the combined influence of slope, forest and cultivated land resulted in the corridor deviating further north than the environmental corridor. The cultivated land in the proximity of the road and railway features resulted in the comprehensive corridor not following them, as was the case with the environmental corridor, but rather along the property boundaries further to the east. Even though the property boundary was weighted very low, it still had an influence on positioning the corridor when no other higher weighted factor was present.

In Zone B the engineering and environmental corridors follow marginally different paths as a result of the difference between how the mining criterion was treated in the two scenarios. In the engineering scenario, the mining criterion was classified as a constraint resulting in the engineering corridor avoiding the mining feature while in the environmental scenario the mining criterion was classified as a factor that should be approached resulting in the environmental corridor crossing the mining feature. In the comprehensive scenario the mining criterion was classified as a factor that should be avoided, this plus the residential criterion that was classified as a factor that should be avoided resulted in the comprehensive corridor differing substantially from the other two corridors.

In Zone C, the three corridors were very similar to each other. In this Zone, the Environmental and Comprehensive corridors followed similar paths. The similarities between these two paths were due to the slope criterion moving the comprehensive corridor south and the wetland criterion doing the same to the environmental corridor.

The length of the corridor was measured and compared with the shortest distance. The shortest distance between the origin and destination substations and the length of the corridor for each scenario is listed in **Table 6.4**. The Engineering Scenario corridor length was the shortest of the three scenarios at 9% longer than the shortest distance. The Environmental Scenario corridor length was 4% longer than the Engineering Scenario corridor length (13% longer than the shortest length). The difference between the Comprehensive Scenario corridor length and the shortest distance was more than twice that of the difference between the Environmental Scenario Corridor length and the shortest distance.

Table 6.4 – Length of Corridor vs. Shortest Distance

Route	Length (m)	Longer than Shortest Distance (m)	% Longer Than Shortest Route
Shortest Distance	33523.626	0	0%
Engineering Scenario	36630.716	3107.09	9%
Environmental Scenario	38043.502	4519.88	13%
Comprehensive Scenario	42608.942	9085.32	27%

6.7 Summary

In chapter 6 the results from the evaluation of the three scenarios as well as the result of approaches such as using fuzzy logic to standardise the input spatial layers was discussed. The conclusions and recommendations arrived at because of these results are presented in chapter 7.

7 Conclusions and recommendations

To select a corridor for an OETL can be a daunting task. Many criteria need to be considered to achieve a balance between stakeholder requirements, damage to the environment and costs. In this research a number of technologies where investigated to test if a SDSS could be assembled that would assist decision makers in the process of selecting a corridor for an OETL.

A process that integrated GIS and multi-criteria decision analysis to select a corridor was modelled in IDRISI Taiga. The model consisted of a number of steps that combined spatial analysis and multi criteria evaluation. The model was used to evaluate various criteria for three different scenarios.

IDRISI Taiga is a raster GIS that has support for importing vector files in ESRI shape file format; converting them to the IDRISI propriety format; spatial analysis; spatial multi-criteria decision making with support for fuzzy membership functions; a modelling environment that allowed the IDRISI Taiga functionality to be assembled and saved into a model that could be executed any number of times.

GIS has become increasingly important in power system planning and analysis. Evidence of this is the number of utilities that rely on automated mapping facilities management (AMFM) systems to manage the power grid. All the SME's consulted during this research felt strongly that any decision-making system should include GIS.

Finding a corridor for an OETL involves considering the location of criteria. GIS is the modern way of performing this mapping function and has largely replaced the activity of overlaying maps on a light table. GIS has developed into a mainstream technology to the extent that today it is more than just a computerised mapping application. GIS has the ability to spatially analyse data and it is these spatial analysis capabilities of the GIS that were used extensively in this research

to combine criteria in order to create new criteria and to evaluate the data. The evaluation process derived new spatial layers that were used as input into subsequent parts of the evaluation process and in so doing solved the complex decision making required to select a corridor for an OETL.

GIS was particularly useful for displaying and visualizing the evaluation criteria as well as the results obtained from the model. The GIS's visualisation capability made it possible to visualise the input criteria resulting in a better understanding of the decision problem. The output from the spatial analysis functions and the results were in the form of spatial layers, these spatial layers were combined with the input spatial layers and presented to the stakeholders as maps.

Using the GIS, the suitability map that was determined for each of the three scenarios, the input criteria and the results (corridor) were overlaid on the 3D physical models resulting in a powerful presentation of many of the aspects relating to the decision. By turning layers on and off in the GIS the 3D presentation enabled the stakeholders to observe the results of the three scenarios in isolation or simultaneously making it easier to compare the results.

The second major component of the SDSS is multi-criteria decision making. This component provided a framework within which all the stakeholders could take part in the decision-making and problem solving process. The strength of the multi criteria analysis framework lay in the fact that it allowed for the opinions of several stakeholders to be taken into consideration and to be processed in a quantitative manner.

The Analytic Hierarchy Process (AHP) used in this research is an example of such a framework. The AHP was used by the SME's in a collaborative group to rank the criteria. The AHP proved useful in determining the weights for each factor as the SME's could relate to the pair-wise comparison and therefore found it easy to use. It was also found that by using the AHP it was possible to get consensus

amongst the SME's as the technique was helpful when the SME's could not agree and it was necessary to reach a compromise.

The weight allocated to each factor was evident in the suitability map that was derived using the weighted linear combination. The constraints were also easily identified in the suitability map as they were represented by a pixel value of 0. The fact that the effect of changes to the input considerations could be seen in the suitability map meant that the SME's accepted the suitability map as a fair reflection of the input criteria rankings.

The suitability map is a spatial layer (map) that reflects the combined effect of all the criteria on the decision. All suitability maps created during this research were standardised to a pixel value in the range of 0-255 thereby making them comparable.

The suitability map could be used as a visual representation of criteria evaluated when it was displayed as raster made-up of colours ranging from red through orange/yellow to green. The suitability map was useful in obtaining an overall perspective of the study area as unsuitable areas were displayed in red against more suitable areas being displayed in green. Just by looking at the suitability map one was immediately able to get an understanding of the area under review to the extent that when the corridor that was determined by a least cost path algorithm was overlaid on the suitability map the choice of the corridor was self explanatory.

The WLC was used to combine the criteria (factors and constraints) into a single spatial layer (suitability map). For this to be possible each of the spatial layers had to be standardised. Fuzzy membership functions were used to standardise each factor distance raster. This research benefitted from using the fuzzy membership functions in the following ways:

- The standardised factor distance raster's were comparable as each raster consisted of pixels with values between 0 and 255.
- Errors in the data were less of a concern as the crisp boundaries where converted to fuzzy zones representing a degree of membership rather than a distinct boundary.
- A third benefit of using fuzzy membership functions was that the extent to which each factor influenced the decision could be controlled. This was achieved by specifying parameters that resulted in meaningful zones around the features. The remainder of the pixels were allocated a value that did not affect the decision.

The methodology used in this research to select a corridor and more specifically the analysis of the multiple criteria required collaboration amongst the SME's. It was necessary for the SME's to discuss/debate the evaluation of the criteria during the pair-wise comparison. Once the SME's understood the pair-wise comparison in relation to the corridor selection process the time taken to perform the comparisons as well as the time taken to perform the overall ranking was reduced. The use of the AHP was therefore dependent on the SME's understanding of multi criteria spatial analysis. Once the SME's realised that the consistency index generated as part of the AHP would highlight any contradictions they made sure that each evaluation pair was not made in isolation but rather in such a manner that it took into account the other comparisons. The consistency ratio proved very valuable in ensuring sensible ranking of the factors.

During this research the analysis was performed on a single study area. If the same process was applied on a different area, the results could differ significantly from those determined in this research. The model was not used by others and therefore it is possible that a different set of results could have been determined if the model were used by others.

The weights used were determined from input obtained from a single group of SME's considering the views of other SME's could have significantly altered the results and could have increased the complexity of selecting a suitable corridor.

In the comprehensive scenario, the environmentally sensitive features were weighted the highest due to the fact that the engineers considered them important so as to avoid possible delays due to environmental legislation and not necessarily due to the fact that the engineers believed that they should be avoided.

A primary consideration when selecting a route for an OETL is the length of the route as the shortest route should result in an OETL that would most likely be the most economical to construct, operate and maintain. The SME's indicated that ideally the length of the selected corridor should not be more than 20% longer than the length of the straight line distance between the origin and destination substations. The length of the corridor was not directly monitored in the model but instead the proxy factor, preferred route, was used to limit the length of the selected corridor. This was achieved by creating a feature along the direct path between the origin and destination substations and weighting the factor high enough to create a zone of lower resistance closer to the preferred route.

The length of the corridor selected for the comprehensive scenario was 27% longer the preferred route. This route was determined by the position of the criteria evaluated and could not be altered other than by changing the criteria or the ranking of the criteria.

The SME's specified the criteria to use when selecting a corridor for an OETL, performed the pair-wise comparison and evaluated the effectiveness of the model. This was done by changing the input parameters, predicting the outcome and then testing if the output corresponded with their prediction.

As stated earlier it can be a daunting task to select a corridor for an OETL, especially for a team without any experience. Even for a team that has experience

in selecting a corridor for an OETL but that has no prior knowledge of an area the sheer number of criteria to consider could also be overwhelming. The SDSS was able to assist the SME's with selecting a corridor for an OETL in the following ways:

- Focused the project team by forcing them to consider and evaluate the criteria together.
- Evaluated multiple criteria spatially.
- Performed scenario analysis by conducting many studies in less time than traditional methods.
- Gave insight into the study area by creating a suitability map that represented a combined view of all the criteria.
- Selected a corridor that avoided criterion that should be avoided and approached criterion that should be approached and that could then be explored further.
- The process of selecting a corridor and the results where presentable to stakeholders including the general public.

The hypothesis that "***a decision support system will assist expert decision makers with selecting an overhead electrical transmission line corridor between 2 substations enabling them to perform scenario analysis by considering various alternatives***" was confirmed.

Future research should be conducted into obtaining multiple corridors from a single suitability map. The fact that only a single corridor was determined in this research limits the practical application thereof. This research should be repeated using different decision makers, criteria and study areas. Future research should consider how lifetime costs could be considered when selecting a corridor for an OETL.

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Appendix A – Presentation: Corridor Selection Spatial Decision Support System

Appendix B – Project Charter: Pilot Project