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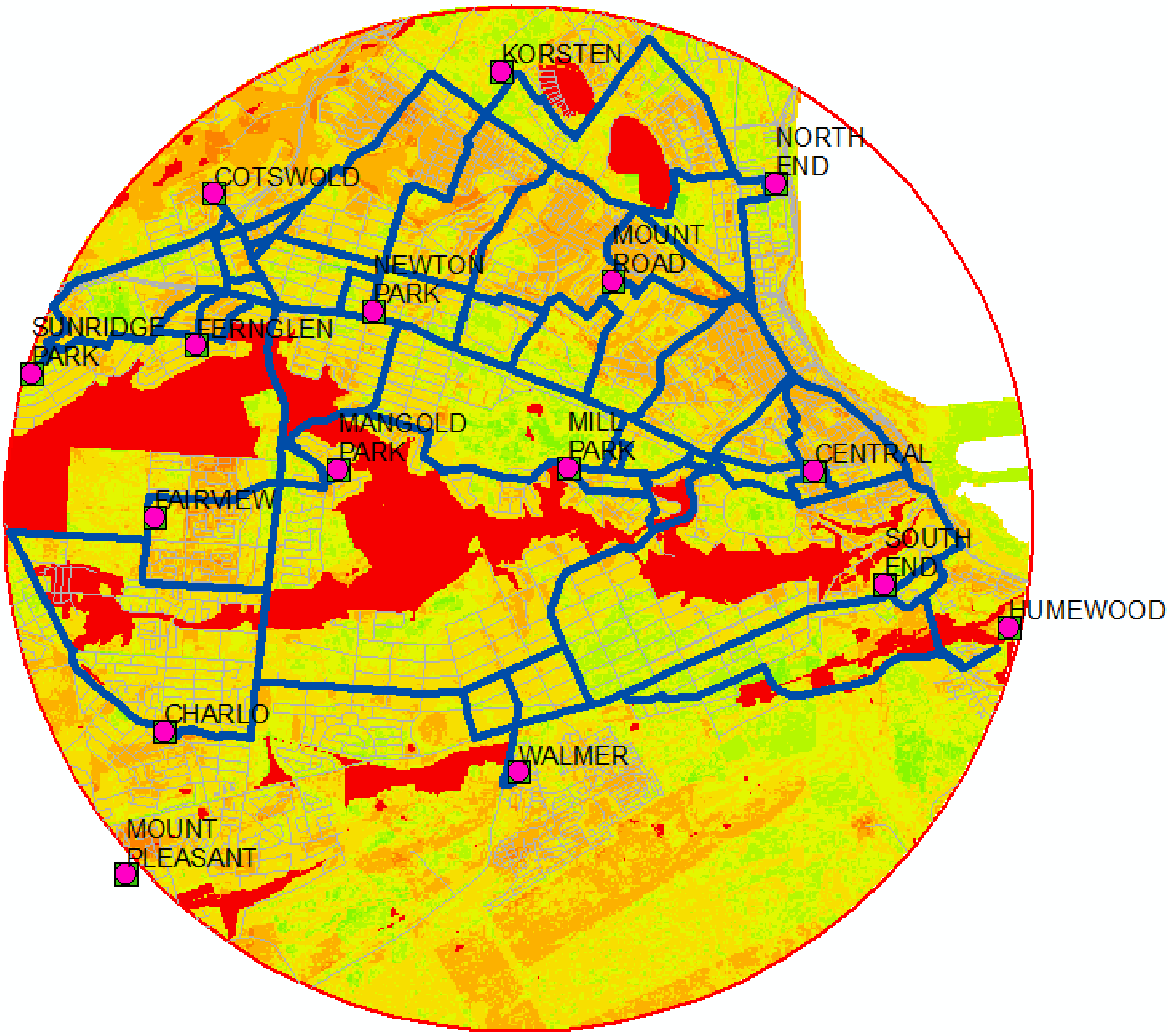
Cycle Route Network Development and Evaluation using Spatial Multi-Criteria Analysis and Shortest Path Analysis



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Acknowledgements

Firstly, I don't think people acknowledge themselves enough for the time and effort they spend on their dissertations or theses. I am of course being facetious, for the most part, but well done me.

On a serious note, I would like to thank Dr Mark Zuidgeest from the University of Cape Town for his guidance and patience during the duration of this study. His enthusiasm of the topic and the potential it has in the field of cycle route network development kept me inspired through the difficult times.

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Last, but definitely not least, I would like to thank my wife for her patience during the compilation of this dissertation. Her unwavering support and constant encouragement was always well received and that push one requires every now and again.

My hope for this method is that it forms an integral part of cycle route network development in the future by providing a transparent, back traceable and engaging tool. By developing routes focused on the needs of cyclists, we can hopefully encourage a shift to more sustainable transport, particularly in urban areas over short to medium distances.

Abstract

The current global trend of urbanisation has resulted in many cities today with growing transportation problems. Locally, South Africa is dealing with both urbanisation and spatial inequalities as a result of the apartheid era, with the poor very often located on the outskirts of urban areas, and therefore far from centres of employment and other amenities. Active mobility in the form of walking and cycling have been suggested as a means to address urban transport challenges, as it simultaneously promotes sustainability and improves the liveability of cities. Moreover, the infrastructural requirements for active mobility are far less when compared to motorised transportation, freeing up more land and funding for the development of community amenities.

Cycling is an efficient way of travelling in urban areas over short to medium distances for a variety of trip purposes, including commuting to work or school, as a feeder to public transport services, to shops, for leisure trips, or tourism. The planning of cycle routes networks is, however, challenging as traditional methods are incapable of adequately dealing with the conflicting objectives of stakeholders and multiple spatial criteria used to measure these. Moreover, the route qualities desired by cyclists are rarely included in the design of routes. Instead a pre- or post-evaluation of route alternatives against the aforementioned route qualities is performed, which once again is not adequately addressed in the current methods given the conflicting objectives and multiple criteria noted earlier. Traditional processes are also criticised for not being open and transparent, leaving many stakeholders dissatisfied. To address these concerns, the proposed method takes advantage of the powerful set of tools for the manipulation and analysis of spatial information provided by Geographical Information Systems (GIS), and the techniques available in Multi-Criteria Analysis (MCA) for structuring decision problems, and designing, evaluating and prioritising alternatives. This combination, known as Spatial Multi-Criteria Analysis (SMCA), can be thought of as a process that transforms and combines geographical data and the value judgements of stakeholders to obtain information for decision making. The advantages gained from combining GIS and MCA results in the development of an effective Spatial Decision Support System (SDSS).

In addition to developing and evaluating a network of cycle routes, the proposed method provides an additional means of prioritising infrastructural requirements using a metric known as Cycle Route Directness (CRD). This compares the network route distance to the Euclidean distance and where the threshold value is exceeded, it can be argued that additional cycle infrastructure is required to reduce the detour by bringing the CRD to below the threshold value.

The study uses SMCA to develop a network of optimal routes, which focuses around the needs of cyclists while taking account of other stakeholder requirements, for a defined area in the metropolitan of Port Elizabeth in South Africa. The relatively flat terrain, temperate climate and proximity of poorer income areas to more affluent areas and places of employment made this an ideal area to act as a proof of concept for the proposed method. The case study showcases the method’s ability to act as a SDSS for cycle route network planning at a strategic level.

List of Abbreviations

CBA	Cost-Benefit Analysis
GIS	Geographical Information System
GME	Geospatial Modelling Environment
LOS	Level of Service
LTSA	Land Transport Safety Authority
LWM	Line Weighted Mean
MCDA	Multi-Criteria Decision Analysis
MCA	Multi-Criteria Analysis
NHTS	National Household Travel Survey
NMBM	Nelson Mandela Bay Municipality
NMT	Non-Motorised Transport
O-D	Origin-Destination
SDSS	Spatial Decision Support System
SMCA	Spatial Multi-Criteria Analysis

Definition of Terms

Activity/Access Street	Any Class 4, 5 or 6 collector, local and pedestrian street where the access function predominates and mobility is restricted.
Arterial	Any Class 1, 2 or 3 vehicle priority, access managed, mobility route whose major function is to provide for movement of person and goods vehicles between cities, towns or urban districts with as few restrictions as possible.
Class	All public roads and paths in the South Africa must be allocated into one of six functional classes, numbered for ease of reference. Each class has a unique function to fulfil.
Collector	A road which collects (or distributes) traffic in a local district. Collectors should not carry traffic passing through the district with destinations elsewhere but can serve as activity spines and streets. Although all roads have a "collection function", the term "collector" is reserved for Class 4 roads.
Cycle	A vehicle with two or more wheels and pedals that is propelled mainly by the muscular effort of the rider. It includes bicycles, tricycles and power-assisted cycles with no more than 200 watts total auxiliary power.
Cycle Facility	Infrastructure that is cycling-specific, such as cycle lanes, paths and parking.
Cycle Lane	A lane marked on a road with a cycle symbol, which can only be used by cyclists.
Cycle Network Plan	A map of the primary cycle route network (see definition below) and a schedule of the cycle infrastructure projects required to develop it.
Cycle Path	An off-road path for cycles. It can be an exclusive cycle path, a shared-use path or a separated path (see definitions below).
Desire Line	A straight line between the origin and destination of a potential cycle trip.
Exclusive Cycle Path	A path that can be used legally only by cyclists.
Grade Separation	The vertical separation of cyclists by a bridge or underpass across a roadway, railway line etc. It contrasts with an at grade intersection or level crossing.
Geographical Information System (GIS)	A software application used to capture, manipulate, analyse and depict all types of spatial data.
Intersection	The point at which two public roads join or cross (a specific type of access).
Leisure Cycling	Cycling done just for the journey itself, not to get to an activity at the journey's end. Sports and recreation cyclists and cycle tourists do leisure cycling.
Level of Service	The quality measure of how well conditions provide for road users. For motor traffic it mainly assesses interruptions to free traffic flow. For cycling, other

	factors seem to be more important such as perceived safety, comfort, and directness of route.
Local Road/Street	A Class 5 road (rural) or street (urban) carrying traffic with origins or destinations in the immediate (local) area with the main purpose of giving access to individual properties.
Mobility Road	A road specifically designed and protected to promote vehicle movement. Priority is given to through traffic movements. Most of the activities allowed on access/activity streets are not permitted on mobility roads.
Multi-criteria Analysis (MCA)	A structured methodology used to determine overall preferences among alternative options based on numerous criteria.
Primary Cycle Network	The most used cycle facilities, designed mainly for trips across town and between suburbs.
Road	A wide way between places. Roads are generally but not exclusively associated with the mobility function (see street).
Rural Area	Any area not defined as an Urban Area. Typically an area of sparse development, mainly given over to nature or farming activities.
Separate Path	A path where the section for cyclists' use is separated from the section for pedestrians' use.
Shared-use Path	A path provided for use by both cyclists and pedestrians.
Spatial Multi-criteria Analysis (SMCA)	A decision support tool combining the use of GIS and MCA to assist in the solving of spatial decision problems.
Street	A town or village "road" typically with access to buildings on one or both sides. A street is exclusively associated with the access/activity function (see road).
Stakeholder	An individual, group, or organization, who may affect, be affected by, or perceive itself to be affected by a decision, activity, or outcome of a project. This may include for example decision-makers, managers, technical experts, and interest groups.
Sustainability	A method of development that meets the needs of the present without comprising the ability of future generations to meet their own needs.
Utility Cycling	Cycling done mainly to get to an activity at the journey's end, such as commuting trips to work, education or shops.
Urban Area	The region surrounding a town, city or similar. Most inhabitants of urban areas have non-agricultural jobs. Urban areas are very developed, meaning there is a density of human structures such as houses, commercial buildings, roads, bridges, and railways.
Urbanisation	The process by which more and more people leave the countryside (rural areas) to live in urban areas.

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1 Introduction

1.1 Motivation for Research

With high rates of urbanisation occurring globally, cities today face many urban challenges and transportation is no exception. Active mobility in the form of walking and cycling have been suggested as a means to address urban transport challenges as it simultaneously promotes sustainability and improves the liveability of cities. Moreover, the infrastructural requirements for active mobility are far less when compared to motorised transportation, freeing up more land and funding for the development of community amenities (Terh & Cao, 2018).

Locally, South Africa is dealing with both the global trend of urbanisation and spatial inequalities as a result of the apartheid era. According to the “Non-motorised Transport Facility Guidelines” (National Department of Transport, 2014), the legacy of apartheid land use planning in South Africa has resulted in urban sprawl and formlessness in land use development, which contradicts some key principles of urban design and transport planning. The result of this is that the poor are very often located on the outskirts of urban areas, and therefore far from centres of employment and other amenities. As South Africa is striving to become a more equitable nation, and the need for more sustainable transport is growing, road planning practices are gradually moving towards a more people focused approach, concentrated on the implementation of Non-Motorised Transport (NMT) and public transport facilities (National Department of Transport, 2014).

Cycling is an efficient way of travelling in urban areas over short to medium distances for a variety of trip purposes, including commuting to work or school, as a feeder to public transport services, to shops, for leisure trips, or tourism (South African Roads Federation, 2015). This is particularly true for the poor who have limited access to transport, where the distances to be travelled exceed what can be considered reasonable to walk, or where public transport is inadequate and/or unsafe. Despite the obvious health benefits, it is a cost-effective mode of travel, assists in easing congestion on the roads, lowers the demand for public transport, and reduces greenhouse gas emissions.

1.2 Problem Statement

The planning of cycle routes and networks should ideally be open and transparent, involving numerous stakeholders, so as to adopt a holistic approach and facilitate buy-in into the planning process. Moreover, it should be focused around the needs of cyclists, with routes exhibiting the qualities necessary to satisfy both existing cyclists as well as encourage cycling as a viable alternative mode of transportation. This being particularly true for commuter-based trips to work, school or shops. From a network perspective, it is important that there is good connectivity or cohesion between cyclists’ starting points and as many destinations as possible, as cycling is only as good as the weakest link in the network (Deffner, et al., 2012).

However, this ideal approach is not always followed. Implementation of cycle routes is often haphazard, leading to routes which are disjointed and incomplete and therefore unsuitable for cyclists. For example, it is not uncommon for cycling infrastructure to be linked to greenfield road projects or road maintenance contracts, without considering the needs of cyclists or other stakeholders. The result of this being not only potentially unsuitable routing but also gaps in the network with inadequate planning or commitment of budget to complete these. Where planning does take place, it is often done in a subjective and/or non-spatial manner. Such an approach may easily overlook route alternatives, which may be more suitable and incorporate the requirements of the various stakeholders concerned. By considering various perspectives early in the planning process, including those of cyclists, technical experts, environmentalists, and institutional bodies (e.g. social and financial considerations by a local government), subjective bias can be removed. Where money and resources are scarce, adequate planning is essential to ensure the responsible allocation of public funds, so as to achieve the greatest benefit with the limited resources available.

To assist in the planning of cycle route networks, the proposed method helps eliminate subjectivity as it is inclusive, transparent, visual and provides quantitative route scores, all of which assist with buy-in into the process. Moreover, as it is possible to solve for an entire network of routes relatively easily, planning can shift from being haphazard and reactive to proactive and complete.

1.3 Foundations of Research

The foundations of this research are primarily based on two publications. The first is the “Cycle Network and Route Planning Guide” (Land Transport Safety Authority, 2004) commissioned and adopted by the New Zealand Land Transport Safety Authority (now New Zealand Transport Agency), which provides a comprehensive guide on cycle route and network planning. This document was informed by a literature review on international best practice, as contained in Boulter et al. (2003). The second is the “Formulation and Evaluation of Transport Planning Alternatives using Spatial Multi-Criteria Assessment and Network Analysis: A Case Study of the Via Baltica Expressway in North-Eastern Poland” (Keshkamat, 2007). In this study multiple criteria are assessed against the requirements of various stakeholders and used to develop the most optimal route between the cities of Warsaw in Poland and Budzisko at the Polish-Lithuanian boarder, using contiguous roads of the existing road network.

1.4 Focus of Study

The focus of this study is to use the principles outlined within the “Cycle Network and Route Planning Guide” (Land Transport Safety Authority, 2004) together with the method developed by Keshkamat (2007) to build and evaluate a network of cycle routes.

The planning of cycle route networks fundamentally consists of four steps. These involve assessing the demand for cycling, identification of the bicycle route network, evaluation of the route alternatives, and prioritisation of the projects required to develop the network. The proposed method focuses on the development of a bicycle route network by evaluating all route alternatives between identified origins and destinations and selecting the optimal routes. Figure 1 provides a brief explanation of each step and highlights where the proposed method fits into the process.

To demonstrate the proposed method, a theoretical case study within the city of Port Elizabeth, which is situated in the Eastern Cape province of South Africa, was undertaken to act as a proof of concept. The relatively flat terrain, temperate climate and proximity of poorer income areas to more affluent areas and places of employment were key factors in its selection.

Although the focus of the study is on the development of bicycle route networks, a brief overview of the remaining steps involved in the planning process will be provided as background information.

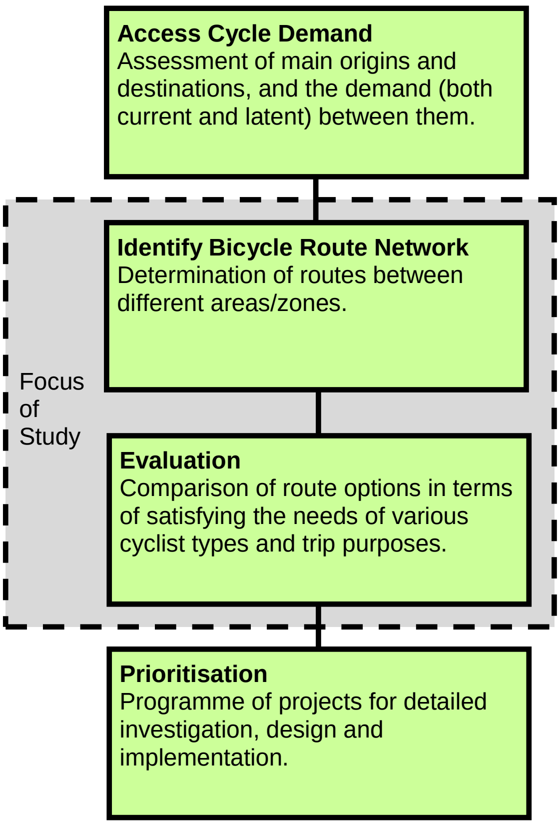


Figure 1: Focus of Study in Relation to Planning Process

Source: Own illustration

1.5 Main Aim and Objectives

The main aim of this dissertation is to develop an objective geo-spatial method for the planning of cycle routes and networks at the strategic level, which takes cognisance primarily of the requirements of cyclists as the end users but also the perspectives of other stakeholders. The theoretical case study undertaken in this dissertation is seen as step 1 of a three-step process. Step 2 involves applying the method to a real-world application. The final step (step 3) involves a comprehensive literature review comparing this method to others in use to identify the advantages, disadvantages and most suitable application/s of each.

Using stakeholder engagement to define, select and weight criteria, and Spatial Multi-Criteria Analysis (SMCA) and Geographical Information System (GIS) software as tools, a Spatial Decision Support System (SDSS) can be created that satisfies stakeholders and promotes trust in the decision-making process by being open and transparent. Planners will be able to take advantage of the graphical interface and quantitative results available through the use of GIS, to objectively select the most optimal routes between Origin-Destination (O-D) pairs, and ultimately develop a cohesive network.

In order to achieve the main aim, the following objectives need to be addressed as part of the study:

- To identify the qualities of a cycle route for a particular trip purpose, and more specifically type, required to meet the needs of cyclists.
- To determine suitable criteria that can be used to measure routes in terms of the above qualities.
- To identify possible qualities and criteria from stakeholders other than cyclists that may affect route selection.
- To suggest how available data can be interpreted and used as a proxy for criteria where the required data is not available.
- To use constraints, costs and benefits derived from the criteria selected in the SMCA process to infer suitability values for routes.
- To use a GIS-based Network Analysis in combination with Routing Suitability Maps to derive optimal routings.

1.6 Requirements of the Study

As with the method developed by Keshkamat (2007), the following requirements are essential to the acceptability of this method among stakeholders and practitioners:

- It must facilitate stakeholder engagement.
- It needs to be universal and adaptable to address multiple criteria from various stakeholders, and not just that considered in the case study provided.
- It must be uncomplicated, transparent and back-traceable.
- It must be user-friendly, cost-effective and time efficient.

Furthermore, to ensure that the method is suitable for a range of applications and data sources, it must be:

- capable of developing either a single route or a network of routes, depending on the requirements of the study; and
- flexible in its use of available data sources as a proxy for criteria where the required data is not yet available.

1.7 Limitations and Future Studies

To showcase the proposed method, a case study area was selected for the development of a cycle route network. Given time and resource constraints, the entire planning process from accessing cycle demand to prioritising cycle facility improvements could not be demonstrated. Because of this, the following limitations of the study are identified:

- No travel demand studies were undertaken to access current and potential demand in the study area selected.
- No assessment was done on existing cycle routes and the number of cyclists using them to assist with planning of routes and prioritisation of facility improvements.
- Information on existing paths was not readily available and therefore was excluded from the model. Paths are often used for leisure trip purposes and may provide shorter links along a route.
- There was no engagement with stakeholders to identify and weight route qualities and criteria. In an attempt to mitigate this, cycle route qualities in terms of the needs of cyclists, and relative importance thereof, was inferred from literature both internationally and locally within the South Africa. Moreover, environmental qualities were included in the form of no-go areas for development, which do not require a weighting as they are protected by legislation and are therefore non-negotiable.
- There was no engagement with cyclists to confirm the suitability of the routes identified by the proposed method.

It is the authors opinion that the above limitations do not compromise the integrity of the method developed for cycle route network determination as they do not affect the qualities or criteria considered in the selection of routes. Moreover, the intention of the study is to act as a proof of concept rather than a commissioned real-world application of the method, and so the correctness of O-D pairs is considered as irrelevant.

Notwithstanding the above, it is recommended that future studies include the above limitations where possible, to showcase real-world applications of the planning process using the proposed method to identify and evaluate routes, and develop a coherent network. This has been done, in part, in a recent parallel study completed by Terh and Cao (2018), where a network was developed in a portion of Singapore using a similar method to that proposed here.

1.8 Dissertation Outline

An overview of the remainder of this dissertation is as follows:

- **Chapter 2** starts with the principles on which cycle route networks should be based, which includes general route requirements, various trip purposes and types together with their specific route requirements, potential cycle route locations, and possible cycle network approaches. This is followed by a brief summary of the planning process followed when developing a cycle network. The chapter concludes with three methods currently used to identify a bicycle network.
- A brief description of MCA in the decision-making process between alternatives and the addition of GIS software to complement the MCA techniques for spatial decision problems is discussed in **Chapter 3**. Previous applications of SMCA, as it is known, is also discussed here.
- **Chapter 4** continues with the proposed method for cycle route network development and evaluation. It begins by listing the software used and provides a description of the study area. Thereafter each section addresses one of the five steps in the proposed method which include the design perspective and associated route qualities, the criteria required and identification of suitable data, the weighting of route qualities and criteria, the process followed in geo-spatial data processing, and finally a check of cycle route directness.
- Finally, **Chapter 5** marks the end of the dissertation with conclusions drawn from the study and recommendations on the way forward.

2 Planning a Cycle Network

2.1 Principles

2.1.1 General Cycle Route Requirements

To create a cycling inclusive environment, some basic requirements are important. According to the "Cycle Network and Route Planning Guide" (Land Transport Safety Authority, 2004), which is based on a literature review of international best practise, cycle routes should exhibit the following qualities:

- **Safety and Security:** Routes should be safe by limiting conflict between cyclists and others, including motorised traffic and pedestrians, and also provide personal security against theft or attack.
- **Comfort:** In terms of design, gentle slopes should be provided where possible, complicated manoeuvres avoided and frequent stopping at intersections minimised. Routes should also be smooth and non-slip.
- **Directness:** Routes should be direct and based on desire lines, with minimal door-to-door delays.
- **Coherence:** Cycle routes should link all potential origins and destinations, be continuous and recognisable and provide consistent safety and security throughout.
- **Attractiveness:** Routes should pass by or through aesthetically pleasing areas where possible. They should also contribute to a pleasant cycling experience by integrating with and complementing their surroundings, enhancing their security and looking attractive.

Locally, within South Africa, these needs are also identified in the National Department of Transport's, "Non-motorised Transport Facility Guidelines" (National Department of Transport, 2014).

2.1.2 Cycle Trip Purpose, Type and Specific Route Requirements

Cycling typically takes place for one of two reasons, either utility or leisure purposes.

Utility cycling occurs when the purpose of a trip is to reach an activity at the trips end (Land Transport Safety Authority, 2004). These types of trips are commonly referred to as commuting trips, and typically occur between residential areas and places of employment, educational institutions, or shops.

In South Africa, cycling as a means of commuting could become an important mode of transportation, particularly for the poor. According to the 2013 National Household Travel Survey (NHTS), of the estimated 13.873 million workers, 145 000 or 1.3% cycled as their main mode of travel all the way to work (Statistics South Africa, 2014). Assuming a minimum of 2 trips per worker per day, this amounts to 290 000 person trips a day across the country. Moreover, according to the survey, a further 2.925 million workers or 20.2% walked all the way to work and it can be argued that a percentage of these would switch to cycling given the opportunity, due to the often large distances between poorer communities and places of employment as a result of the apartheid era. Combined NMT therefore contributes approximately 21.5% as the main mode of transport used by workers within South Africa, the majority being within metro and urban areas (Statistics South Africa, 2014). Based on the above, commuter cycling in South Africa has a great potential benefit for increased mobility and access to job opportunities, provided cycle route networks are properly planned and implemented, and cycling is encouraged as a viable alternative mode of transport.

Leisure cycling differs in that these trips are taken for the journey itself (Land Transport Safety Authority, 2004). Typical trip types include sport, recreation cycling and touring cycling. Countries with favourable weather conditions, including South Africa, lend themselves towards leisure cycling and a relatively high demand for these trips can be expected.

When planning cycle routes, the route qualities vary depending on the trip purpose, and more specifically type. Table 1 provides a summary of the specific route requirements for each trip type according to the "Cycle Network and Route Planning Guide" (Land Transport Safety Authority, 2004).

Table 1: Summary of Cycle Trip Types and their Specific Route Requirements

Trip Type	**Brief Description**	**Specific Route Requirements***
Neighbourhood cycling (purpose – utility and leisure)	Trips to local schools and shops, and children playing on their bikes.	• Safety : low traffic volumes and speeds, good separation from traffic on busy roads, facilities to improve safety when crossing busy roads such as traffic signals. • Security : good lighting for evening trips. • Comfort : minimal gradients.
Commuter cycling (purpose - utility)	Trips to work, education facilities (mainly high schools and tertiary education facilities), or shops.	• Safety : intersection types that minimise conflict with other traffic and facilities which give them their own space. • Security : good lighting for evening trips. • Directness : shortest possible routes to minimise travel time. • Coherence : continuous routes and networks linking as many destinations as possible. • Comfort : gentle gradients and minimal intersections.
Sport cycling (adults) (purpose - leisure)	Trips taken for physical exercise. Cyclists often travel in groups and like to ride two abreast.	• Safety : generous road widths. • Comfort : minimal delays. • Physically challenging routes with steep gradients.
Recreation cycling (purpose - leisure)	Trips taken for the experience and to enjoy the scenery.	• Safety : limit conflict with motorised traffic. • Security : minimise potential for theft and attack. • Comfort : minimal gradients, complicated manoeuvres avoided and limited unnecessary stopping. • Attractiveness : pleasant, attractive and interesting routes, often past attractions.
Touring cycling (purpose - leisure)	Trips taken over long distances with camping gear and supplies. Cyclists often travel in groups or pairs.	• Safety : generous roadside shoulders. • Attractiveness : pleasant, attractive and interesting routes.

* Requirements listed are those to be considered during the planning of routes. Infrastructure requirements such as types of cycle paths (e,g. inlane versus grade separated), road surface quality,

traffic calming measures, and secure bike parking facilities are excluded as these are seen as design requirements necessary to ensure route compliance.

It is important to emphasise that the route requirements in Table 1, although specific to the various trip types, are generalised. These may vary depending on the experience level, age and/or gender of cyclists. Although it is important to maintain the specific route requirements to satisfy existing experienced users, if cycling is to be promoted as viable alternative mode of transport, provision for new users with basic competence needs to be made. Therefore, as far as practically possible, as many of the general route requirements discussed under Section 2.1.1 should be included to both retain existing users and attract new ones.

Local conditions may also influence the specific route requirements and need to be taken into consideration. For example, in high risk areas, security may be an important route requirement for all trip types. The placement of routes adjacent to busy areas with high visibility or well-lit areas at night may therefore supersede other route requirements.

2.1.3 Cycle Route Locations

Cycle routes are made up of interconnected roads and/or paths. Given the functional hierarchy of roads and paths for either mobility or access, each classification lends itself to certain trip types. For example, commuter trips often take place along arterial roads as these are the most direct links between key O-D pairs (Land Transport Safety Authority, 2004). On the contrary, paths through parks or along foreshores are generally better suited to recreational cycling given that they are attractive and free of motorised traffic. Despite each location lending itself to a certain trip type/s, this is not to say that the locations are mutually exclusive. Paths may provide a shorter link for commuter cyclists. Similarly, an arterial may have an attractive vista along one or both sides. It may however require that infrastructure improvements are made to ensure the various specific route requirements are met.

A summary of possible cycle route locations, extracted from the LTSA (2004), is provided in Table 2. The road classification, according to functional hierarchy, for the New Zealand roads and South African equivalents is as compared in the “South African Road Classification and Access Management Manual” (Committee of Transport Officials, 2012).

Table 2: Possible Cycle Route Locations

Roads		**Paths**
New Zealand (NZ)	**South Africa (SA)**	**NZ and SA***
National roads	Principal arterials	Operating railways
Primary arterials	Major arterials	Disused railways
Secondary arterials	Minor arterials	Watercourses
Collector roads	Collector streets	Foreshores
Local roads	Local streets	Reserves and parks

* The terminology for paths is interchangeable between New Zealand and South Africa.

2.1.4 Cycle Network Approaches

The "Cycle Network and Route Planning Guide" (Land Transport Safety Authority, 2004) outlines five (5) possible approaches to developing a cycle route network. These, in summary, are:

1. Every street :

Cyclists' trip origins and destinations are as complex of those of car users. All streets are used to access facilities beside them, whether or not they have specific cycling facilities.

If all streets and intersections provide quality cycling conditions then there is no need to provide primary cycling routes. However, this is rarely, if ever, the case. As roads are arranged in a hierarchy so that longer-distance traffic is concentrated on higher-standard roads for efficiency and to manage traffic effects, a similar approach is usually required for cycling.

2. Roads or paths :

The degree to which cycle facilities will be segregated for motorised traffic is a fundamental consideration. Possible types of segregation include:

- Isolated paths.
- Paths next to roads separated by kerbs, islands or vegetated strips.
- Marked space on the roadway, such as cycle lanes and road shoulders.
- Fully shared mixed road space.

While primary cycle networks are based on one type of facility, most cycle networks contain a mixture of different facility types. A fully segregated primary cycle network is only practical on greenfield sites when planning new suburbs or townships. In already-existing towns, it is impractical to develop an off-road path network, so cycle networks are developed around the established road network (mostly arterials).

3. Dual networks :

Dual networks provide two different types of cycle route network, for example, one based on urban arterial roads and the other on cycle paths or backstreets. The arterial network would generally cater for more experienced commuter cyclists whereas the path based network would generally cater for novice or recreational cyclists.

Funding constraints may often limit the possibility of dual networks. The Level of Service (LOS) provided by each network type to the different cyclist groups should then be assessed.

4. Hierarchy approach :

As with roads, cycle routes are sometimes assigned hierarchies based on trip length and user type. Cycle routes in regional or district networks may be classified as regional, inter-urban or tourist. In urban areas, cycle routes may be classified as principal, collector or local.

Principal routes are for longer-distance movement and therefore direct, whereas collector routes distribute cycle traffic between principal routes and local origins and destinations. Local routes form the very first or last portion of a route from the collector route to each individual origin or destination.

5. Needs approach :

In the needs approach, the option that best provides for cyclists' needs in each situation is chosen.

This approach aims at achieving the best results for cyclists and other stakeholders within the context of all prevailing opportunities and constraints. It may include any of the options or locations discussed earlier, as well as dual provision over some sections if it is needed and feasible.

6. General recommendations:

On greenfield sites, neighbourhood streets should be designed for slow mixed traffic. Moreover, cycle routes should be more closely spaced and permeable than motorised traffic networks. This can be achieved by adding traffic free links.

Paths should be positioned in parks and reserves and should link homes to significant local destinations. This is so that children and novices do not have to mix with faster or busier traffic.

In existing areas, the exiting road hierarchy usually provides for the basis of the primary cycle network, which is mostly along arterials.

2.2 The Planning Process

A well planned and designed bicycle facility is a benefit to society (National Department of Transport, 2003). Not only does it increase mobility and access to job opportunities, particularly for the poor, but it has the potential to lessen the burden on government bodies by encouraging a modal shift away from cars and other motorised travel, thereby reducing the need for additional road infrastructure and the demand for public transport services over short to medium distances.

To establish what is to be provided for cyclists as well as where it is to be provided, good information is required. This may include the purpose for which people cycle, their competence to handle a variety of conditions, where they wish to ride and how many people currently cycle or wish to cycle (Land Transport Safety Authority, 2004). To assist in gathering the information, the New Zealand Land Transport Safety Authority outlines a process that can be followed. A summary of this, as modified in Chapter 6 of the "Cycling-Inclusive Policy Document : A Handbook" (Zuidgeest, et al., 2009), is provided below:

Access Cycle Demand and Identify Route Network

1. Develop a base map of land use, trip origins and destinations.
    a. Map land use, typically using city/district planning information.
    b. Assess their importance as cycling trip generators.
    c. Map desire lines.
2. Map existing facilities, routes, cycle related accidents and cyclist volumes.
    a. Map existing cycle facilities.
    b. Count and map cycle traffic and parked bicycles.
    c. Map cycle related accidents.
    d. Consult and/or survey bicycle users.
    e. Assess trip purposes and types of cyclists.
3. Map main infrastructure barriers and identify missing connections.
4. Assess and understand latent demand.

Evaluate Cycle Route Options

5. Evaluate route options in terms of satisfying the needs of various cyclist types and trip purposes.

Prioritise Bicycle Network Structure

6. Define and establish priorities for a bicycle network structure using qualitative and quantitative methods.

Each of the above steps provides useful data when planning cycle routes and networks. It is important to note that the level of detail in which the various steps are addressed is largely dependent on the local context, and the availability of data and resources (Zuidgeest, et al., 2009). Ideally all steps should be followed and preferably in collaboration with the different stakeholders involved in the process.

2.2.1 Assigning of Origins and Destinations

When planning for a transportation mode, trip generation or the assignment of origins and destinations is generally accepted as the first step. Origins are defined as places where people start their journey whereas destinations are places people want to travel to. Of course, all origins become destinations and vice-versa. Typical origins and destinations include:

- Residential areas.
- Educational institutions (i.e. schools and universities).
- Shopping centres.
- Sports facilities.
- Employment concentrations, such as large companies and business parks.
- Tourist attractions and natural areas.
- Leisure and entertainment facilities.
- Public facilities.
- Major public transport hubs and interchanges (e.g. railways, bus, tram, metro).

When assigning origins and destinations, city/district planning documents are a very useful source of primary data (Land Transport Safety Authority, 2004). According to the LTSA (2004), these include information relating to existing land use, road hierarchy, land use zones and growth areas, major residential subdivisions, and commercial or community developments.

Once the origin and destination locations are identified, these are to be mapped either manually on a paper based road or land use map, or alternatively electronically on maps in a GIS system (Zuidgeest, et al., 2009).

To determine the relative importance of cycling trip generators, the LTSA (2004) describes various methods and provides the advantages and disadvantages of each. These in summary include using: census data; visitor numbers to popular locations, attractions or facilities (either from existing data or counting); counts of parked bicycles at popular locations such as schools; existing travel survey information; or questionnaires.

With the locations plotted, straight lines connecting the main cycle origins and destinations, known as desire lines, can be plotted. As noted by Zuidgeest et al. (2009), using the information gathered on the importance of the trip generators, the desire lines can be weighted according to the potential strength of trip generation between O-D pairs. This can once again either be done manually or electronically as noted above. The result is what is known as a preferential or theoretical network and allows planners to identify high potential links where the demand for cycling is likely to be significant (Deffner, et al., 2012). An example of an intuitive weighting of desire lines is shown in Figure 2.

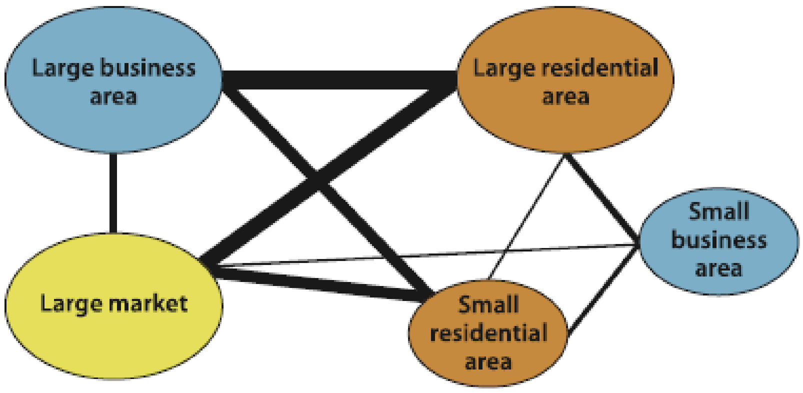


Figure 2: Intuitive Creation and Weighting of Desire Lines

Source: (Zuidgeest, et al., 2009)

2.2.2 Identification of Cycle Routes and their Utilisation

The desire lines developed during the assigning of origins and destinations in step 1 above do not represent the actual routes or number of cycling trips between O-D pairs. Rather they represent potential travel demand between important origins and destinations for cyclists based on the relations between them (Zuidgeest, et al., 2009).

Existing cycle routes can be identified by plotting existing cycle facilities, consulting with bicycle users, and/or conducting questionnaires.

The utilisation of routes can be estimated and determined using numerous methods. A first assumption of potential cycle demand across an area can be achieved using the road hierarchy method (Land Transport Safety Authority, 2004). According to the LTSA (2004), the assumption is that cycle demand along a particular link in the road network will be directly proportional to the to the motorised traffic, meaning that busy roads could be expected to carry large volumes of cycle traffic (assuming appropriate cycle conditions). This can later be refined by conducting cycle counts or performing questionnaires on a sample set of users. Cycle crash data, over a long period of time, can indicate those routes that cyclists have difficulty negotiating safely and as a result may have low utilisation and require infrastructure interventions.

Trip purpose and cyclist type assist with identify the network type required as well as the route qualities between or origins and destinations. Methods for identifying user type and trip purpose include:

- consultation;
- travel surveys;
- manual counts;
- counting bicycles at key destinations;
- census data; and
- questionnaires.

2.2.3 Barriers and Identification of Missing Links

The desire lines developed in Section 2.2.1 represent the shortest distance between main cycle origins and destinations. In reality, however, routes follow roads and/or paths and are therefore longer. In certain instances, logical O-D connections are prevented as a result of barriers such as highways, waterways, railways, swamps, large industrial estates, unsafe areas or sections of road that cyclists perceive to be hazardous (Land Transport Safety Authority, 2004). These barriers result in missing links in the existing network. As noted by Zuidgeest et al. (2009), special attention needs to be paid to these when developing the bicycle network as special provisions may have to be made to desired connections.

2.2.4 Assess and Understand Latent Demand

Latent demand, according to the LTSA (2004), is defined as the potential new cycle trips that are currently suppressed, but that would be made if cycling conditions were improved. It can be assessed as a result of specific route improvements or to the whole network, assuming it is fully developed (Land Transport Safety Authority, 2004).

According to the study by Zuidgeest et al. (2009), measuring latent demand requires understanding factors that influence people's choice to adopt cycling. The study notes that surveys of cyclists and non-cyclists, which ask about the main constraints affecting the decision to cycle or not, are helpful in this case. Decision makers can bring some of these factors under control and induce latent demand by, for example, providing good quality and safe bicycle facilities, or remove prejudices about cycling through effective marketing (Zuidgeest, et al., 2009).

2.2.5 Evaluate Cycle Route Options

The "Cycle Network and Route Planning Guide" (Land Transport Safety Authority, 2004) outlines various ways to evaluate cycle route options in terms of how they satisfy the needs of the various cyclist types and trip purposes likely on each route. These, in brief, are:

- Needs assessment : qualitative assessment of the route qualities required for each trip purpose.
- Audits : formal process for identifying deficiencies in provision for cyclists. The four (4) different types of audit are a cycle audit, road safety audit, cycling safety audit, and vulnerable road user audit.
- Level of Service (LOS) assessment : cycling LOS is based on a significant volume of empirical research on cyclists' views and reactions to specific road environments.
- Cycle review : an audit process based on professional engineering and user perceptions to evaluate how well existing facilities meet cyclists needs and provides a thorough process of identifying improvements. This is done by collecting data, performing a LOS assessment, and a deficiency analysis.

Further details on each of the above as well as their respective advantages and disadvantages can be found in the guideline document.

The LTSA (2004) recommends that a mix of methods be used when evaluating routes. The needs assessment is highlighted as an important method as it is qualitative and therefore able to deal with all route qualities, some of which can only be assessed in a qualitative manner. According to the guide, the cycle review LOS method appears to be the most useful for a quantitative assessment.

2.2.6 Prioritise Bicycle Network Structure

According to the LTSA (2004), the prioritisation of cycle route development is more of an art than a science. The "Cycle Network and Route Planning Guide" (Land Transport Safety Authority, 2004) briefly describes a number of criteria to be considered when prioritising routes together with their advantages and disadvantages. A summary of the possible criteria which can be considered is provided below:

- LOS/cycle review : priority given to routes or sections thereof with the lowest LOS or to projects which provide the most LOS improvement.
- Existing usage numbers : prioritise improvements to existing routes according to demand (i.e. the greater the demand the higher the priority).
- Crash records : prioritise according to crash cost savings that can be achieved.

- Blockage removal : this method assigns priority to projects where removing a blockage would achieve the greatest increase in cyclist numbers or other cyclist benefits. Blockages can include, for example, safety at roundabouts or physical barriers causing excessive deviations
- Demonstrable achievement : priority is given to the easiest or cheapest projects in a programme.
- Area consolidation : in this method priority is given to providing a consistently high LOS in one area and thereafter the focus is shifted to another area.
- Quality demonstration projects : flagship projects that showcase attractive, high quality facilities are prioritised in the hopes that other communities will want to emulate them.

As with the evaluation methods discussed earlier, the guide recommends that several criteria be assessed together when prioritising projects. For example, the LOS criteria can be usefully combined with cycling usage data and cross-compared with crash data and project costs.

2.3 Methods of Identifying a Bicycle Network

The previous section provides an overview on: assessing cycle demand in terms of cycling trip origins and destinations; existing cycling infrastructure and the number of cyclists using them; barriers preventing logical O-D connections; and the concept of latent demand.

This section follows on in the planning process by using the data collected and discussing some of the current methods available for identifying bicycle routes and networks. This is by no means a comprehensive literature review of all existing methods as this is not the intention of the study. Rather, an overview of the methods identified during the literature review that are unique in their approach is provided. This in preparation for the proposed method presented in Chapter 4.

2.3.1 Elastic Thread Method

The Elastic Threat Method identifies where residents of certain groups of families or households travel to. A brief summary of the process, as described by Zuidgeest et al. (2009), is provided below:

1. A map is laid out on soft board or similar material and the main origins and destinations, as defined in Section 2.2.1, marked within each land use zone. For cycling, residential areas are subdivided into allotments of 200 to 400 households and the centre point of each is marked as the departure point (aside: for walking, allotments of 50 to 100 households are used).
2. The centre points of the origins are linked to the main daily destinations using thin elastic bands. Bicycle links are only pinned if they exceed a defined minimum distance, as shorter trips are typically made by walking. Once all origins and destinations are linked, a star shaped pattern is formed.
3. Pins are used to bundle the elastic threads along logical streets and paths people would take, creating a fairly accurate picture of cycling movements in the study area.

A graphical representation of the above steps can be seen in Figure 3.

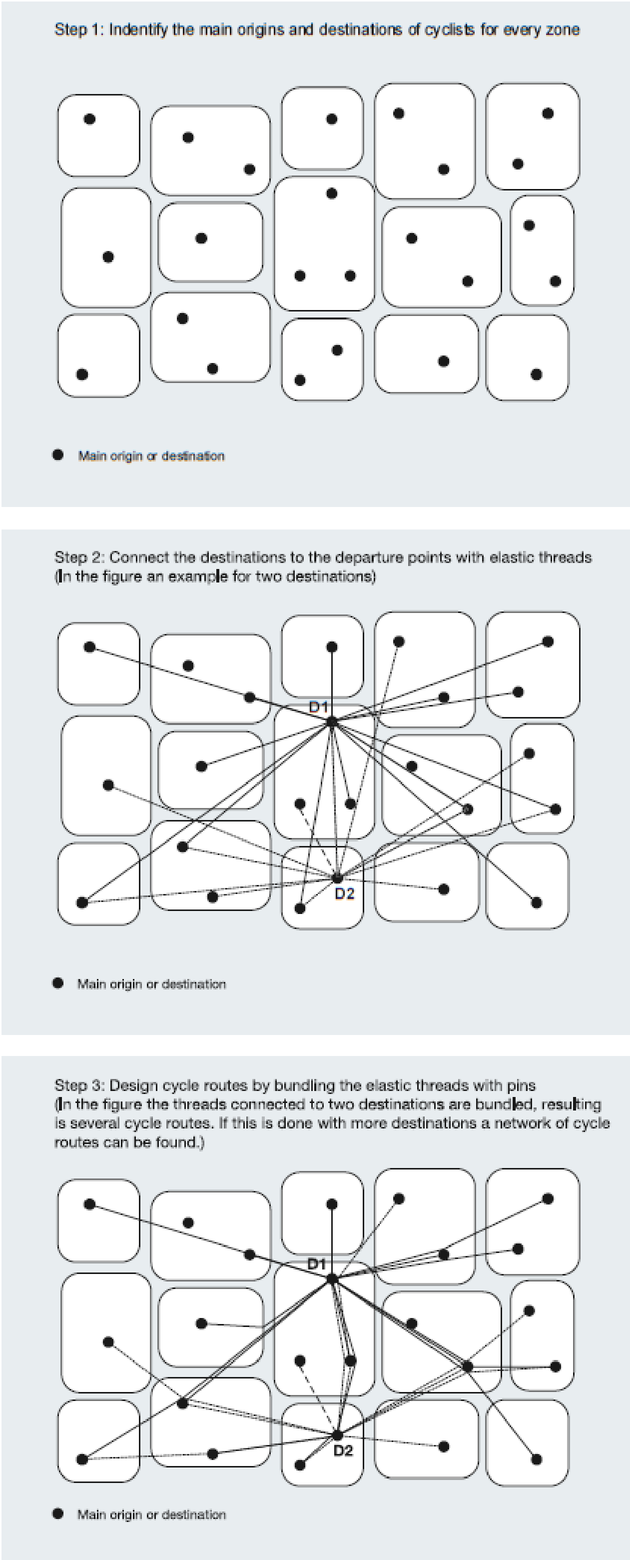


Figure 3: Example of Elastic Thread Method Applied

Source: (Zuidgeest, et al., 2009)

As noted in the study by Zuidgeest et. al (2009), the greater the number of elastic threads on one route the more users would benefit from the route being short, safe and attractive. Long detours will result in the elastic threads being tensioned, and if one breaks, it shows an excessive deviation from the preferred cycling behaviour.

Computer software such as Star Analysis, or a common GIS can also be used to assist with this method (Zuidgeest, et al., 2009). Using a GIS, steps 1 and 2 can be simulated by automatically generating desire lines between O-D pairs, which can even be weighted according to the demand for travel between them.

2.3.2 Strategic Outline Method

According to Zuidgeest et al. (2009), the Strategic Outline Method provides a quick scan and systematic framework for groups of experts to define a bicycle network using local knowledge and expertise in bicycle planning. Using a road or land use map, planners together with stakeholders are able to develop a sketch map of (Zuidgeest, et al., 2009):

- main (potential) bicycle trip origins such as large residential areas of a certain socio-economic class;
- main (potential) bicycle trip destinations such as large employment, industrial or commercial areas; and
- main barriers such as highways or insecure areas (refer to Section 2.2.3).

The above can also be plotted electronically using a GIS to systematically overlay digital maps to create a base map for the strategic outline session.

Once the base map is created, a strategic outline of the bicycle network is developed in a participatory manner with stakeholders by linking all origins and destinations, while avoiding the main barriers. This is the start of the actual network design process, and area connections and routes can be refined by conducting field visits for example (Zuidgeest, et al., 2009). If time permits, this method can be expanded to cover the complete network planning process discussed in Section 2.2. An example of this method applied to a corridor in Quito, Ecuador is shown in Figure 4.

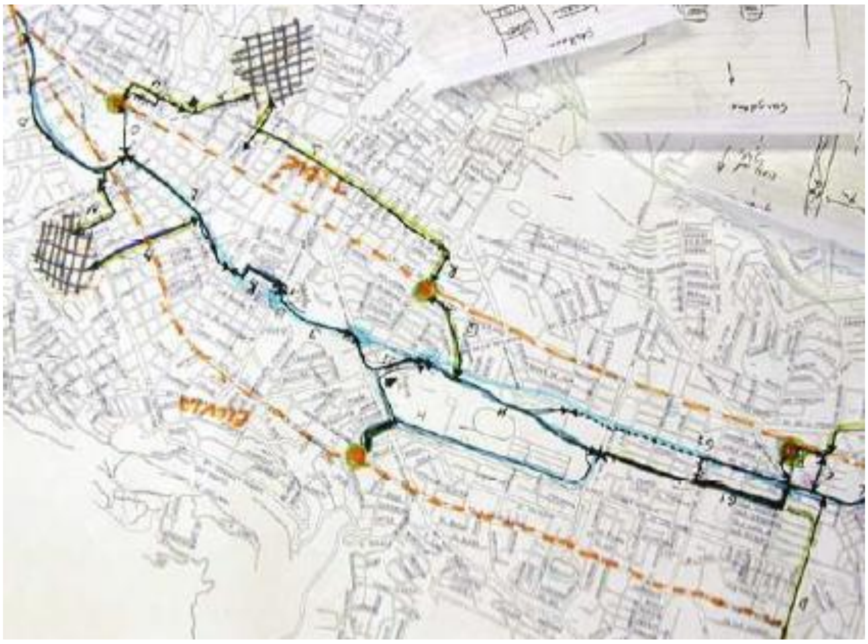


Figure 4: Strategic Outline Method Applied in Quito, Ecuador

Source: (Zuidgeest, et al., 2009)

Zuidgeest et al. (2009) note the advantages of the method being that it is very simple to apply, it does not require as much time or resources as the elastic thread method, and it creates ownership of the network created by involving stakeholders through the entire process.

2.3.3 Cycling Through Method

The Cycling Through Method can be used to automatically identify missing links in a network as discussed in Section 2.2.3. According to Zuidgeest et al. (2009), the method works by calculating the differences between the network and Euclidian (straight line) distances between O-D pairs. The differences are then translated into demand densities using the detour factors calculated and the attraction between O-D pairs. These are then plotted using a GIS, with darker areas highlighting the need for additional links.

To use the method, an actual O-D matrix for cycling trips for at least part of the study area is required (Zuidgeest, et al., 2009). An actual application of this method as used in Dar es Salaam is shown in Figure 5.

Figure 5: Cycling Through Method Applied in Dar es Salaam, Tanzania

Source: (Zuidgeest, et al., 2009)

2.3.4 Supply- and Demand-Based Method

The method presented by Rybarczyk and Wu (2010) uses GIS and multi-criteria decision analysis at a network level, both of which are further discussed in Chapter 3, to evaluate and identify cycle routes using supply- and demand-based criteria.

The supply-based criteria used to define the suitability of road conditions for cycling typically include engineering type roadway variables such as roadway width, traffic volume, ground surface conditions, and vehicle speeds. These are then assessed using one of the many quantitative level of service type models, briefly touched on in Section 2.2.5, such as Bicycle Level of Service (BLOS), Bikeway Quality Index (BQI) or Bicycle Compatibility Index (BCI). The scores and /or grades calculated for each road segment are then plotted to the road network with the assistance of GIS.

Demand-based criteria are those that influence cycle demand. They are selected according to access and demand requirements (e.g. population distribution along roads provides a good index for estimating potential demand for and access to a route) as well as the needs of cyclists in terms of both route qualities and access to key destinations (e.g. proximity of businesses, schools, recreational areas and parks have a positive effect on road utilisation whereas proximity of crime hotspots have a negative impact on road utilisation due to safety concerns). Criteria selected are then ranked in terms of relative importance and thereafter assigned to road segments. Assignment to a road segment only occurs where the criteria fall within a defined radius of the segment, as there needs to be suitable access to and demand for a route to be justifiable. A demand potential index then needs to be calculated to integrate all demand criteria, which involves standardising all values between zero (0) and one (1), weighting criteria according to their assigned rankings, and finally summing the weighted standardised scores per road segment. The resultant index values are again plotted to the road network using GIS.

By comparing the two maps, it is possible to both evaluate existing cycle routes and identify new routes against supply- and demand-based criteria. Figure 6 provides a comparison of the resultant supply (measured according to BLOS grades) and demand (measured according to demand index) maps for a case study of the method applied to Milwaukee City, Wisconsin in the United States of America. The lower the BLOS grade (i.e. A < B, etc.) the better the safety conditions for cyclists, whereas the higher the demand index, the greater the demand potential.

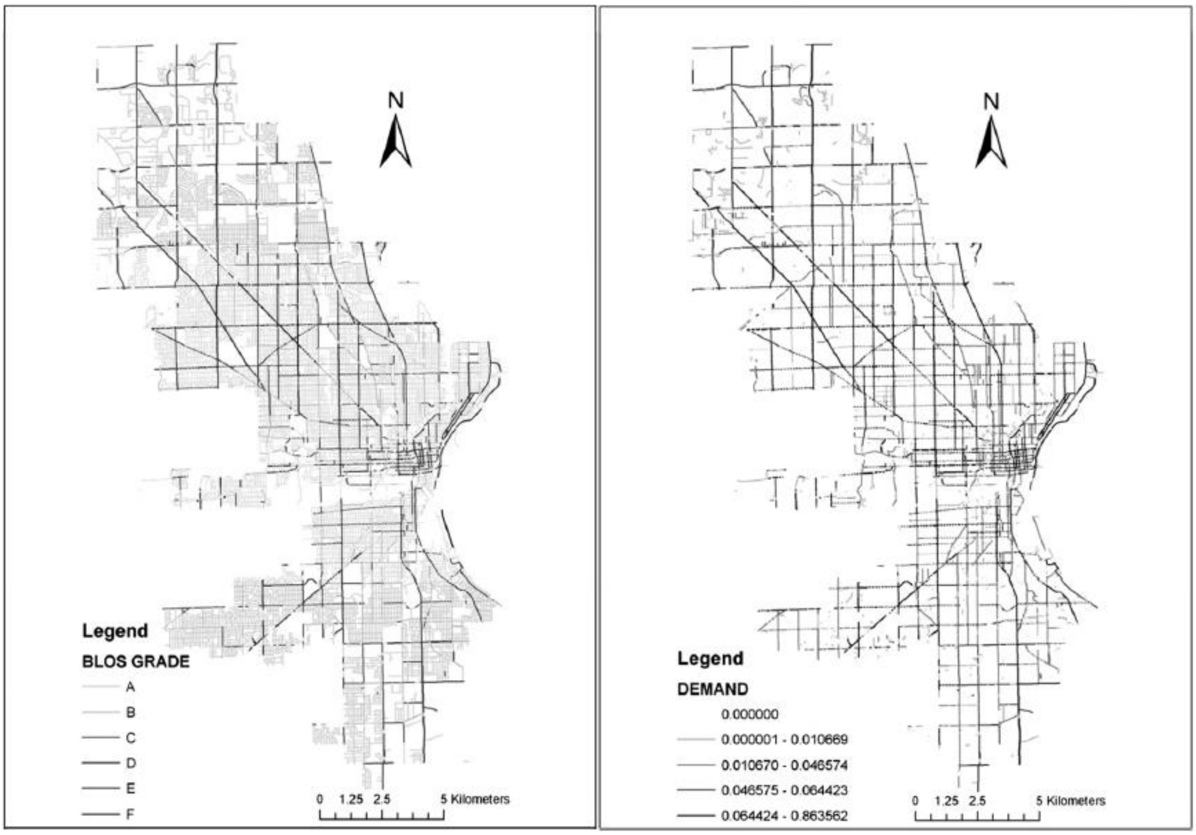


Figure 6: Comparison of BLOS and Demand Indices for City of Milwaukee

Source: (Rybarczyk & Wu, 2010)

The outcome of the case study proved that both supply- and demand-based criteria need to be taken into consideration as road segments with a high level of service do not necessarily have a high demand and vice-versa. For example, arterial roads have a poor level of service given the traffic volumes and speeds, heavy vehicle traffic, etc. associated with these facilities. However, they have a high demand index given the population and key destination distribution along them.

2.3.5 GIS-based and Grid Cell Method

Larsen et al. (2013) proposed a method which uses GIS to combine indicators into a grid-cell model that identifies priority locations for new cycling infrastructure. The method consists of the following four steps (Larsen, et al., 2013):

1. Identification of indicators (for which data are available) that can be used to prioritise locations for infrastructure investments.
2. Impose a grid and spatially aggregate the indicators and associate them to the grid's cells.
3. Aggregated grid cell indictors are combined into a "prioritisation" index, where the higher the index value, the more appropriate the grid cell is for cycling infrastructure investment.
4. Finally, grid cell characteristics, information on existing infrastructure, and disaggregate data are combined to infer the most appropriate types of interventions for particular locations.

A case study of the method by Larsen et al. (2013) was undertaken in Montreal, Canada. Five indicators were selected for the study, namely: number of observed cycling journeys, number of potential cycling journeys, priority segments identified by cyclists, location of cycling collisions, and discontinuities in current cycling network. Only four of the indicators were aggregated to grid cells, leaving discontinuities in the current cycling network, also known as "dangling nodes", as disaggregate data. This because unlike the other indicators, dangling nodes are not sufficient in and of themselves to prioritise a grid cell (i.e. other factors affect suitability other than presence, such as amount of infrastructure required to make a connection).

An extract from the study which shows specific infrastructure interventions for different sections of the network is shown in Figure 7 below.

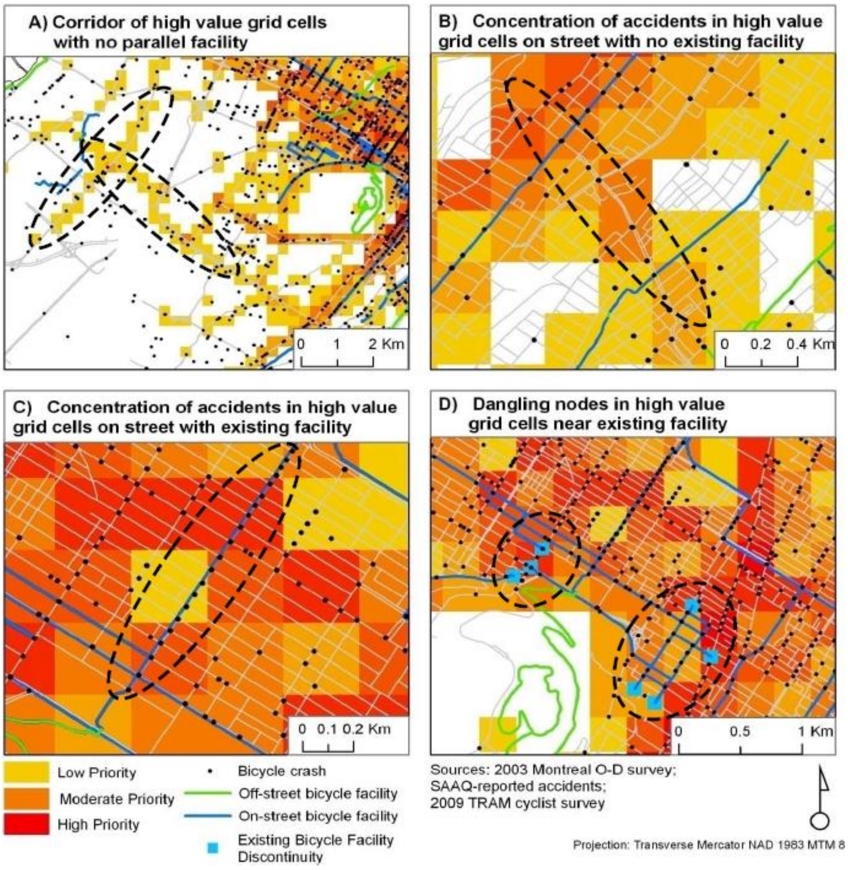


Figure 7: Specific Infrastructure Interventions at Identified Locations

Source: (Larsen, et al., 2013)

3 (Spatial) Multi-Criteria Analysis

3.1 Background

Multi-Criteria Analysis (MCA) provides a valuable set of techniques, which when combined with procedures can be applied to the complex decisions that need to be made when choosing between alternatives, by acting as a decision support system. This combination of techniques and procedures is a form of MCA commonly known as Multi-Criteria Decision Analysis (MCDA). It acts as a support system by dividing a decision into smaller, more understandable parts which can be analysed, and finally combines these parts into a meaningful solution. This is particularly useful given the difficulties humans face in handling large amounts of complex data in a consistent manner.

MCA has many advantages over informal judgement unsupported by analysis. According to the Department for Communities and Local Government (2009) in the United Kingdom:

- it is open and explicit;
- the objectives and criteria selected are open to criticism and change if deemed to be unsuitable;
- scores and weights, when used, are also explicit and are developed according to established techniques. They can also be cross-referenced to other sources of information on relative values, and amended if necessary;
- performance measurement or rating of alternatives against criteria can be sub-contracted to experts to remove potential subjectivity if left to stakeholders;
- facilitates a means of communication between stakeholders and sometimes between stakeholders and the broader community; and
- it provides an audit trail.

When dealing with spatial decision problems, such as choosing between alternative site or route locations, conventional MCA is extremely limited. To address this shortfall, Geographical Information Systems (GIS) have been used together with MCA techniques to develop Spatial Decision Support Systems (SDSS) known as Spatial Multi-Criteria Analysis (SMCA).

The following sections provide an overview of MCA and SMCA, as well as a summary of past applications of SMCA in various fields and for various applications.

3.2 Multi-Criteria Analysis

The basic aim of MCA techniques is to analyse a number of choice alternatives against conflicting objectives and multiple criteria (Carver, 1991). The objectives are those of key stakeholders, which may vary based on their respective interests. The criteria are those selected and agreed by the stakeholders and are used to measure the performance of the alternatives against the objectives. As noted by the Department for Communities and Local Government (2009), the outcome of the analysis can either be a single most preferred alternative, a ranking of the alternatives, a short-list of alternatives for subsequent detailed assessment, or simply to distinguish between those which are acceptable and unacceptable.

The involvement of key stakeholders in establishing objectives and criteria, estimating relative importance weights of criteria and, to some extent, the rating of alternatives against the criteria is a key feature of MCA and also one that may lead to inherent subjectivity (Department for Communities and Local Government, 2009). This, however, can be mitigated by including objective, quantitative data such as actual pricing or involving neutral experts to evaluate the performance of the alternatives against the criteria. Despite concerns of possible subjectivity, MCA provides a level of transparency not found in other assessment techniques, such as Cost-Benefit Analysis (CBA) (Department for Communities and Local Government, 2009).

One limitation to be aware of is that MCA cannot show whether an action adds more welfare than it detracts (Department for Communities and Local Government, 2009). In other words, the “best” option may detract welfare from the status quo, so doing nothing could in principle be preferable. This is an important point to be aware of when evaluating alternatives.

A full application of MCA typically involves eight steps as set out in Figure 8.

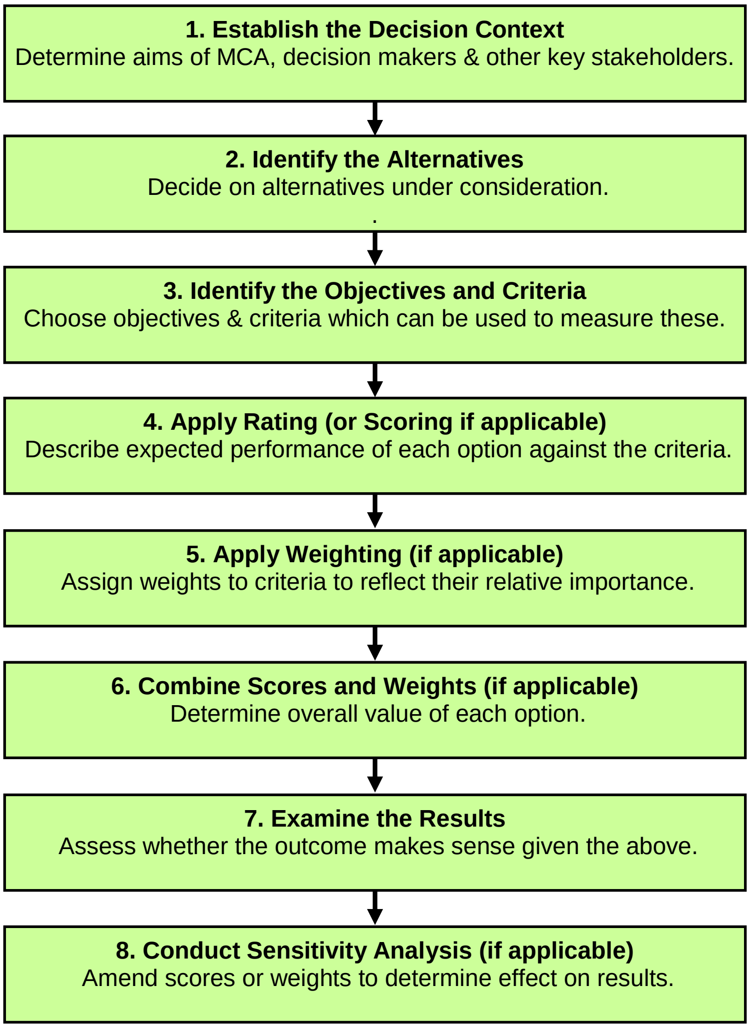


Figure 8: Typical Steps Followed in Full Application of MCA

Source: Adapted from (Department for Communities and Local Government, 2009)

Once the decision context, alternatives, objectives and criteria have been decided, an evaluation or performance matrix can be created. An example of such a matrix set up to evaluate a number of toaster brands is shown in Figure 9.

Table 4.1 Performance matrix

Options	Price	Reheat setting	Warming rack	Adjustable slot width	Evenness of toasting	Number of drawbacks
Boots 2-slice	£18				☆	3
Kenwood TT350	£27	✓	✓	✓	☆	3
Marks & Spencer 2235	£25	✓	✓		★	3
Morphy Richards Coolstyle	£22				☆	2
Philips HD4807	£22	✓			★	2
Kenwood TT825	£30				☆	2
Tefal Thick'n'Thin 8780	£20	✓		✓	★	5

A tick indicates the presence of a feature. Evenness of toasting is shown in *Which?* on a five-point scale, with a solid star representing the best toaster, and an open star the next best. The family eliminated from consideration all the toasters that scored less than best or next best.

Figure 9: Example of Completed Performance Matrix

Source: (Department for Communities and Local Government, 2009)

In the example provided, each row represents an alternative and each column describes its performance against a specific criterion. The performance can either be measured quantitatively (i.e. numerically) or qualitatively (i.e. colour coding or "bullet point" scores), as can be seen in the example provided, which includes a combination of both.

In a basic MCA, where steps 5, 6 and 8 are excluded, the evaluation or performance matrix may be the end result and stakeholders are then left with the responsibility of deciding the extent to which the objectives are met (Department for Communities and Local Government, 2009). In more advanced applications, more sophisticated MCA techniques are available in which a numerical analysis is applied to the performance matrix in two stages. The first stage, known as scoring, is necessary to enable a meaningful comparison of criteria which are often measured on different scales (Carver, 1991). To do so a number of different standardisation techniques are available to normalise the criteria scores. The Department for Communities and Local Government (2009) notes that scales between 0 and 100 (or 1) are often used where the lowest score is theoretically 0 and the highest 100 (or 1). The second stage, known as weighting, is necessary as different criteria typically have different levels of importance. An overall assessment of each alternative is then calculated by combining the aforementioned two stages using mathematical routines. The simplest and most common being a weighted average of the scores, also known as linear additive models (Department for Communities and Local Government, 2009). Other popular approaches include multi-attribute utility theory, the analytical hierarchy process, and outranking methods.

After the analysis of the performance matrix a sensitivity analysis is generally required given potential uncertainty surrounding the validity of the inputs, particularly the weighting of criteria. It provides a means for examining the extent to which vagueness affects the final overall results and in so doing helps to resolve disagreements between stakeholders (Department for Communities and Local Government, 2009).

There are many existing MCA techniques, with more continually being developed. To assist with the selection of an appropriate method, the Department for Communities and Local Government (2009) suggests that the following are some of the considerations that need to be taken into account:

- internal consistency and logical soundness;
- transparency;
- ease of use;

- data requirements not inconsistent with the importance of the issue being considered;
- realistic time and manpower resource requirements for the analysis process;
- ability to provide an audit trail; and
- software availability, where needed.

The progression form MCA to SMCA for spatial decision problems is discussed in the following section.

3.3 Spatial Multi-Criteria Analysis

Chakhar and Mousseau (2008) define spatial multi-criteria decision making as the application of MCA in a spatial context where alternatives, criteria and other elements of the decision problem have explicit spatial dimensions.

Since the late 1980s, MCA has been coupled with GIS to enhance spatial multi-criteria decision making (Chakhar & Mousseau, 2008). GIS provides stakeholders with a powerful set of tools for the manipulation and analysis of spatial information, however, this functionality is limited as the spatial analytical functionality of most GIS packages lies in the ability to perform deterministic overlay and buffering operations. (Carver, 1991). According to Carver (1991), although ideal for performing spatial searches based on nominally mapped criteria, when multiple and conflicting objectives and criteria are concerned, they are limited. He notes further that such overlay procedures can do little more than identify areas which simultaneously satisfy all the specified criteria and that there is nothing in the analysis that informs the user which individual site(s) offer the most promising characteristics for development (i.e. no ranking). Additional procedures, based on MCA, are therefore required for structuring decision problems, and designing, evaluating and prioritising alternative decisions (Malczewski, 2006). This combination of GIS and MCA is often referred to as GIS-MCDA (i.e. given the combination of techniques and procedures) or Spatial Multi-Criteria Analysis (SMCA). Fundamentally, SMCA can be thought of as a process that transforms and combines geographical data and the value judgements of stakeholders to obtain information for decision making.

The advantages gained from combining GIS and MCA results in the development of effective Spatial Decision Support Systems (SDSS). As noted by Carver (1991), despite GIS having certain spatial analysis techniques, only the addition of advanced spatial analysis capabilities provided by MCA, the expertise of the decision-maker and a suitable user interface can constitute a SDSS.

SMCA problems can be classified according to two approaches. Malczewski (2006) defines these as multi-attribute and multi-objective, whereas Zucca et al. (2008) quotes Keeney (1992) as distinguishing them between alternative-focused and value-focused. Multi-attribute or alternative-focused problems consist of a select number of alternatives, predetermined or developed, which undergo an evaluation process after which a recommendation is made (Zucca, et al., 2008). In these types of problems, the specification of objectives and criteria are only done once the alternatives exist. As noted by Malczewski (2006), solving this type of problem is a selection process as opposed to a design process. Multi-objective or value-focused problems differ in that the objectives and criteria are determined first and used in the selection of alternatives. These problems are therefore continuous in that the best solution may be found anywhere within the region of feasible solutions (Malczewski, 2006). When considering the aforementioned, it is evident that in multi-attribute problems the focus is on the evaluation of alternatives, whereas the focus in multi-objective problems lies in what is desired (Zucca, et al., 2008).

According to Sharifi (2006), alternatives in a spatial decision problem can be described by a defined set of maps providing information on each criterion. He continues noting that a spatial decision problem can be visualized as an “evaluation table of maps”, which has to be transformed into one final ranking of alternatives. As shown in Figure 10, for this to be achieved it is necessary to not only aggregate in the thematic space (function f) but also in the spatial dimension (function g). These two operations can either be performed simultaneously or in succession. If performed in succession, this can be carried out in two different orders. If Path 1 is followed, the spatial information per alternative / criterion pair is aggregated first to a non-spatial value (i.e. the aggregated criterion score per alternative is determined), after which traditional MCA techniques are applied to calculate the final utility for each alternative. Following Path 2, first the criteria per alternative are aggregated using MCA techniques to obtain a suitability map for each alternative, thus reflecting the performance of the alternative across the space. Thereafter each map is aggregated to a single non-spatial value. According to Zucca et al. (2008), Path 3 is the most direct approach when the two operations occur simultaneously. In this case all the information is processed manually by the decision maker/s alone and converted into a ranking.

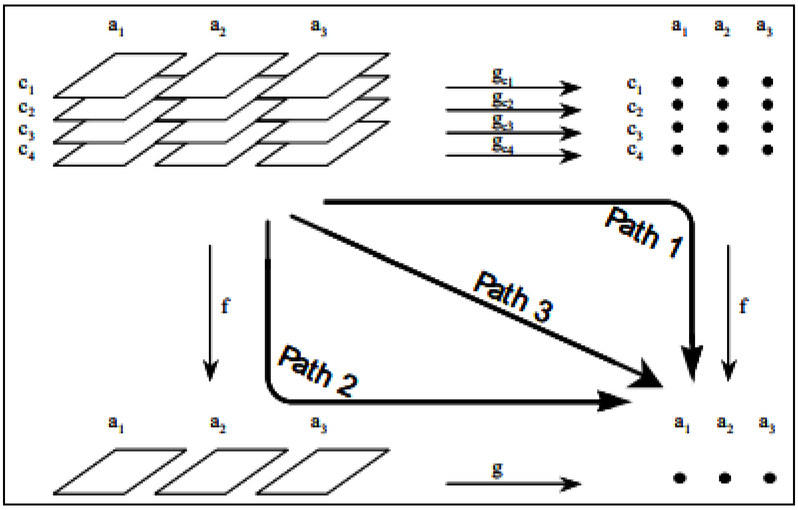


Figure 10: Different Methods of Aggregation in SMCA

Source: (Sharifi, 2006)

In van Herwijnen's 1999 study as well as a later study by Sharifi et al. in 2006, it is noted that each of the paths described have advantages and disadvantages (cited in Zucca et al. (2008)). Path 2 is regarded as being particularly advantageous as it is possible to perform a MCA using both spatial criteria and non-spatial criteria, without losing the spatial dimension. Path 3, although being the most direct, may be subject to error given the difficulty in processing multiple and disparate spatial criteria, and bias if stakeholders are not involved in the weighting of criteria.

There are many strengths and weaknesses in the use of SMCA when solving spatial decision problems. The weaknesses can, however, often be managed and the strengths make it applicable to solving most spatial problems. The findings from a literature review of the strengths and weaknesses by Barendse (2016) as well as some of those already addressed above is provided in Table 3.

Table 3: Strengths and Weaknesses of SMCA in Solving Spatial Problems

Strengths	Weaknesses
• It provides a structured and streamlined approach to solving complex spatial problems, involving multiple and conflicting planning objectives.	• The method is quite complicated and incorrect implementation thereof could have significant consequences, such as unfruitful expenditure or reduced operational efficiencies of a new facility.
• SMCA is very transparent in the manner in which goals, criteria and weightings are selected and incorporated into the evaluation of the alternatives, as a trail of evidence is available on how the final decision is made. This strengthens the accountability and reliability of the decision-making process.	• Stakeholders can highly influence the results through their perceived importance of the evaluation criteria resulting in a significant level of inherent bias in the decision-making process.
• Both qualitative and quantitative criteria can be considered simultaneously.	• Data requirements within SMCA are very extensive, thus the availability and quality of data included in the analysis can impede on the value of the final results.
• Spatial and none spatial criteria can be considered without losing the spatial dimension.	• The choice of pixel size in the evaluation may lead to loss of information, making this decision crucial to the reliability of the outcomes.
• It provides a valuable mechanism for conversation between stakeholders as well as an effective means of public participation by allowing public input. The latter may also provide valuable feedback to stakeholders regarding public sentiment.	• The MCA component may have the inability to determine whether the best solution is better or worse than the status quo.

According to Carver (1991), it is important to note, however, that GIS and MCA techniques are merely tools which provide a means to an end. Without the knowledge and expertise of the operator and decision-maker, and without appropriate data, such tools would be useless.

3.4 Applications of SMCA

A literature review by Malczewski (2006) on the use of GIS-based MCA during the period 1990-2004 revealed that it had been applied in the following fields:

- Environmental planning and ecology management.
- Transportation.
- Urban and regional planning.
- Waste resource management.
- Hydrology and water resources.
- Agriculture.

- Forestry.
- Natural hazard management.
- Recreation and tourism management.
- Health care resource allocation.
- Housing and real estate.

The analyses within the above fields varied and consisted of land suitability, plan/scenario evaluation, site search/selection, resource allocation, vehicle routing and scheduling, impact assessment, and location-allocation.

The analysis in this study, as previously noted, focuses on routing in the transportation field, and more specifically on the generation of cycle route networks. A recent parallel study by Terh and Cao (2018), showcases a similar application of SMCA for a case study in Singapore and is the only other published example of its kind found by the author.

4 Proposed Method for Cycle Route Network Development and Evaluation

This study follows on from the methods of identifying bicycle networks discussed in Section 2.3 and uses the principles of SMCA discussed in Chapter 3 to propose an alternative to these and others currently being used.

In terms of the classification of SMCA problems discussed in Section 3.3, the proposed method classifies the problem of developing a cycle route network as multi-objective or value-focused as the best routes may be found anywhere within the region of feasible solutions. Of the possible paths which can be followed when evaluating criteria, path 2 was followed given its ability to perform a MCA using both spatial and non-spatial criteria, where required, without losing the spatial dimension.

The method developed facilitates stakeholders engagement and provides a SDSS for developing and evaluating cycle routes and networks in a spatial, transparent and objective manner. Stakeholder engagement is facilitated as route qualities are defined and weighted by stakeholders, and their involvement is further encouraged in the identifying of missing links in a network, The method is transparent and objective as stakeholders are involved in the selection and weighting of route qualities, and the output of this can be visually seen in the raster maps created for each quality (and criteria used to define the qualities) as well as the final suitability map created during the SMCA process. Moreover, the quantitative scores assigned to routes allows for an objective comparison of alternatives.

The method is based on works completed by Keshkamat (2007), who used it to formulate and evaluate route alternatives for the Via Baltica expressway in north-eastern Poland. This study is unique to that of Keshkamat's in that a network of routes is developed as opposed to a single route between a defined O-D pair. A brief overview of the main aim, objectives and requirements of the method are discussed in Chapter 1.

A flowchart of the key steps within the method is shown in Figure 11. As illustrated in the flowchart, the five (5) main steps of the bicycle route network design method are:

1. Define the perspective (goal) of the analysis and select qualities (sub-goals) appropriate to it.
2. Identify criteria which represent the qualities chosen, and source and process the spatial data that can be used to measure these criteria.
3. Weight the criteria within each quality and the qualities in relation to the perspective based on stakeholder engagement and policy visions.
4. The above steps are then used to perform the SMCA. Thereafter the network analysis process is performed to generate an optimal cycle route or route network as required.
5. Compare the network route length between O-D pairs as a ratio of the Euclidian distance and where the value exceeds a defined threshold, add a link/s to reduce the network length. Where additional links are required and viable for inclusion, the network analysis portion of Step 4 is to be redone.

The output generated using the method can also be compared to existing or predetermined future routes. Moreover, a sensitivity analysis of the scoring approach and weightings can be done and the implication on the routing assessed.

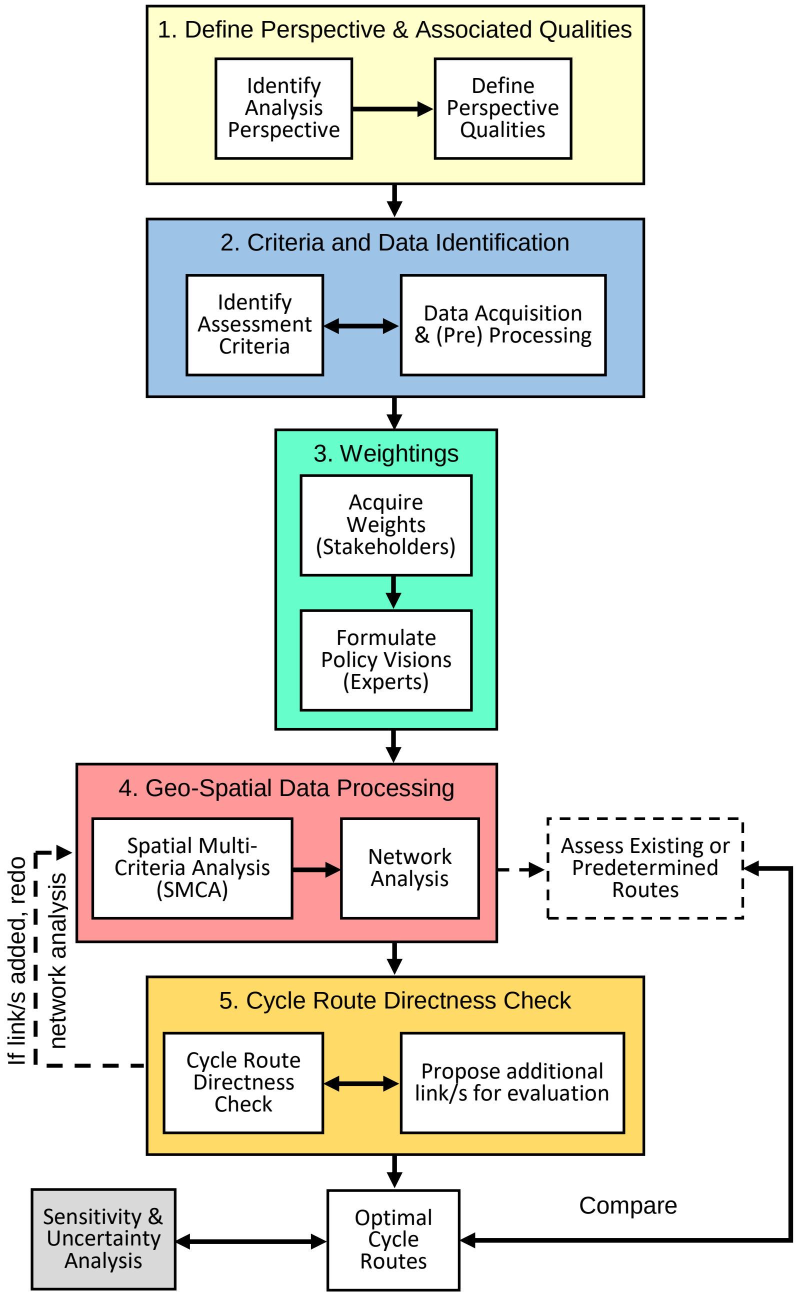


Figure 11: Basic Flowchart of Method

Source: Own illustration

4.1 Software Used

A number of different software packages were used throughout the study. A list of these in the applicable steps is provided below.

- Step 2 – Data Acquisition and (Pre)Processing:
    - ArcGIS Map 10.3.1
    - Google Earth Pro
    - Civil Designer 2015

- Step 4 – Spatial Multi-Criteria Analysis:
    - ILWIS 3.8.5
- Step 4 – Network Analysis:
    - ArcGIS Map 10.3.1
    - R 3.2.2 (statistical computation platform)
    - Geospatial Modelling Environment 0.7.4.0
- Step 5 – Cycle Route Directness Check:
    - ArcGIS Map 10.3.1
    - Microsoft Excel 2016

To showcase the method, a case study area was identified to act as a proof of concept. The area selected and details of each of the key steps are further discussed in the following sections.

4.2 Study Area

The case study area selected, illustrated in Figure 12 falls within Port Elizabeth, which is situated in the Eastern Cape Province of South Africa.

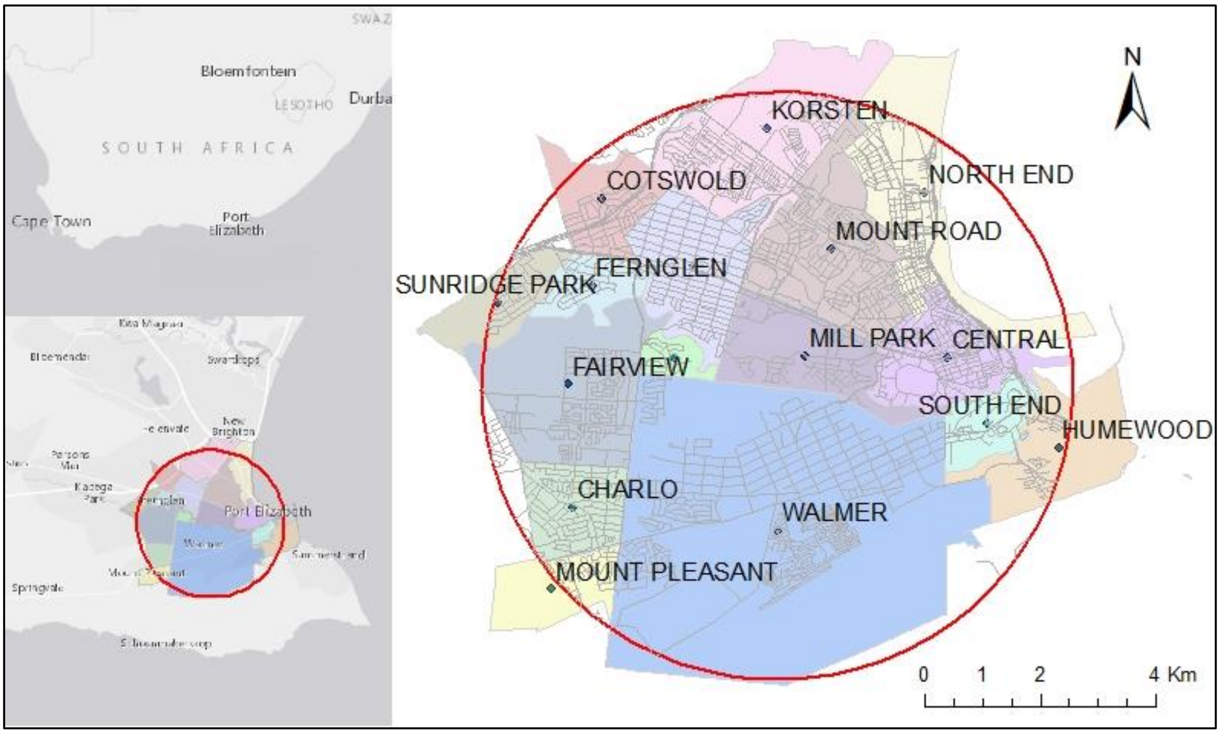


Figure 12: Study Area including Allotment Areas and Road Network

Source: Own illustration

The study area includes a broad range of income areas ranging from a low income, high density township development in Walmer at the lowest end of the scale to high income, low density suburbs with Mill Park and parts of Walmer at the upper end of the scale. The area was selected given its favourable typography and the proximity of the poorer income areas to more affluent areas and other places of employment. The communities of Walmer Township, Central, North End and Korsten typically have lower income households. Employment opportunities and educational institutions can be found within these areas and the other suburbs within the study area.

The circle shown demarcates an area with a radius of approximately 5km. According to the New Zealand Travel Survey for the period 1997/98, this is the median trip length for commuting cyclists within New Zealand (Land Transport Safety Authority, 2004). Locally, this is further substantiated by the South African National Department of Transport in the “Pedestrian and Bicycle Facility Guidelines” (National Department of Transport, 2003) where it is noted that most cyclists would prefer to cycle distances shorter than 5km, but proceeds to say that poorer communities unable to afford public transport may travel further. Moreover, an analysis of trip length distribution (TLD) for cyclists in Dublin, Ireland revealed that over 75% of trips to work are less than 8km, with a further approximately 9% of trips occurring over a distance of 8-10km (Dublin Transport Office, 2006). The peak distance range for work trips in the study was 4-6km, with approximately 25% of trips occurring in this range.

As the radius of the study area is a Euclidian distance, it is considered to be sufficiently large to accommodate the range of network trip lengths that can reasonably be expected.

4.2.1 Cycle Demand

The “Cycle Network and Route Planning Guide” (Land Transport Safety Authority, 2004) defines the primary cycle network as the most commonly used cycle facilities, designed mainly for trips between suburbs and across town. Taking this into consideration together with the fact that there is currently a very low demand for commuter cycling, it was assumed for the case study that there is an equal latent demand to travel between each of the suburbs. The exact location within each suburb was taken as it’s respective centroid, which is represented by a dot as shown in Figure 12.

4.2.2 Ecology

The ecology considered was that of wetlands (blue), protected areas (purple) and critical biodiversity areas (red). In terms of future development, protect areas are legally protected under the Protected Areas Act (PPA) in South Africa and cannot be developed on. Critical Biodiversity Areas differ in that they are not protected under the PPA and therefore may be developed on if certain requirements are met. Lastly, wetlands are also legally protected under the National Environmental Management Act (NEMA) and National Water Act and are therefore defined as no-go areas. Both protected areas and wetlands can therefore only be crossed with a bridge which has footings either side of the protected area. Figure 13 shows the locations of these within the study area.

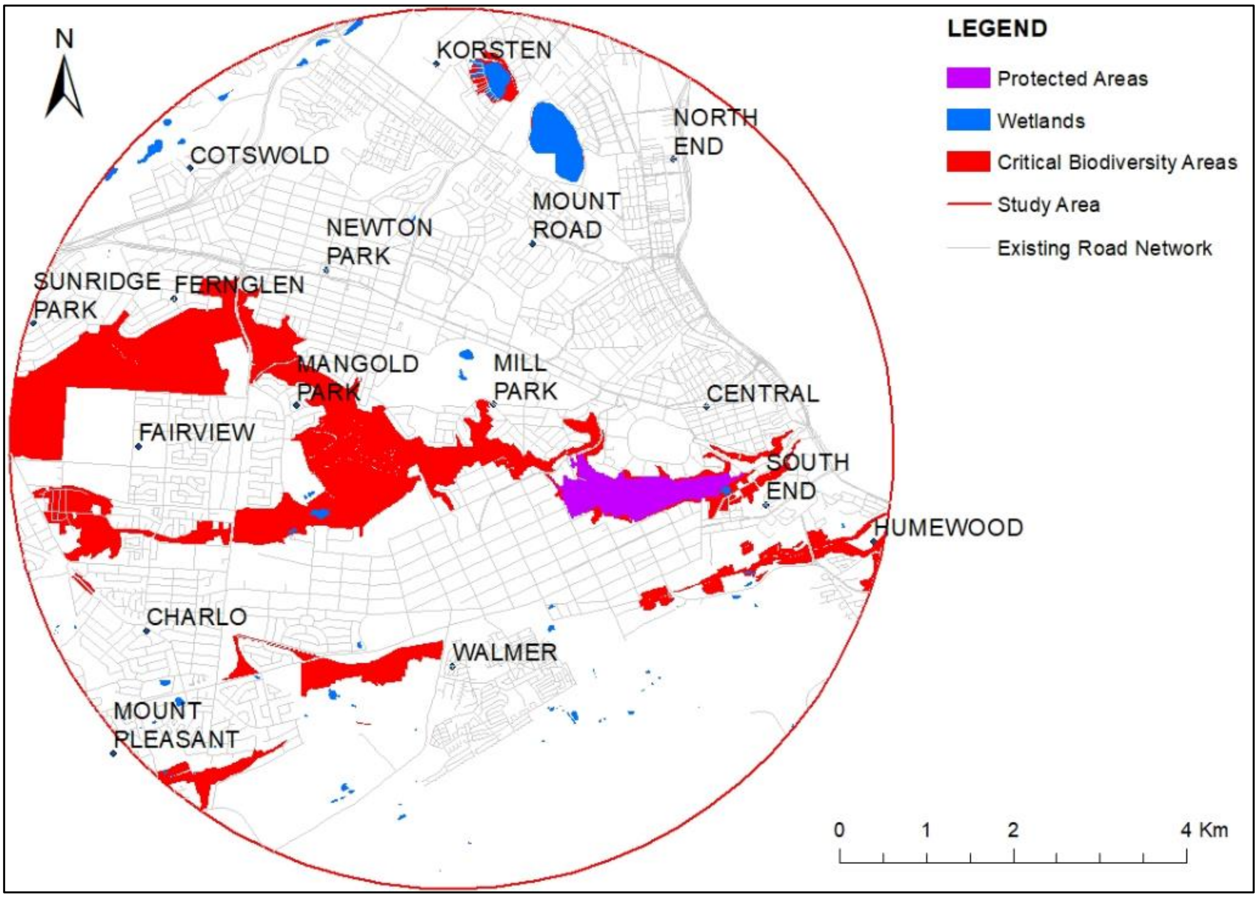


Figure 13: Ecology Considered within Study Area

Source: Own illustration

4.2.3 Topography

To assess the topography of the site in terms of cycling suitability, an analysis was done to derive gradients in intervals according to contours based on a 20m grid survey. The intervals considered were in increments of 1% from 0% to exceeding 5%. According to the "Pedestrian and Bicycle Facility Guidelines" (National Department of Transport, 2003), gradients in excess of 5%, especially over sustained distances, are undesirable.

From Figure 14 it can be seen that the site is characterised by relatively flat sections between steep slopes. The steep section running through the middle of the site corresponds with the critical biodiversity and protected areas shown in Figure 13 above. This area is known as the Baakens River Valley. This valley cuts the area in two with only limited crossing opportunities (i.e. 5 within the study area). To the north of the Baakens are slopes leading from the plateau area down towards the sea. To the south of Baakens are hilly areas resulting in relatively steep gradients in places.

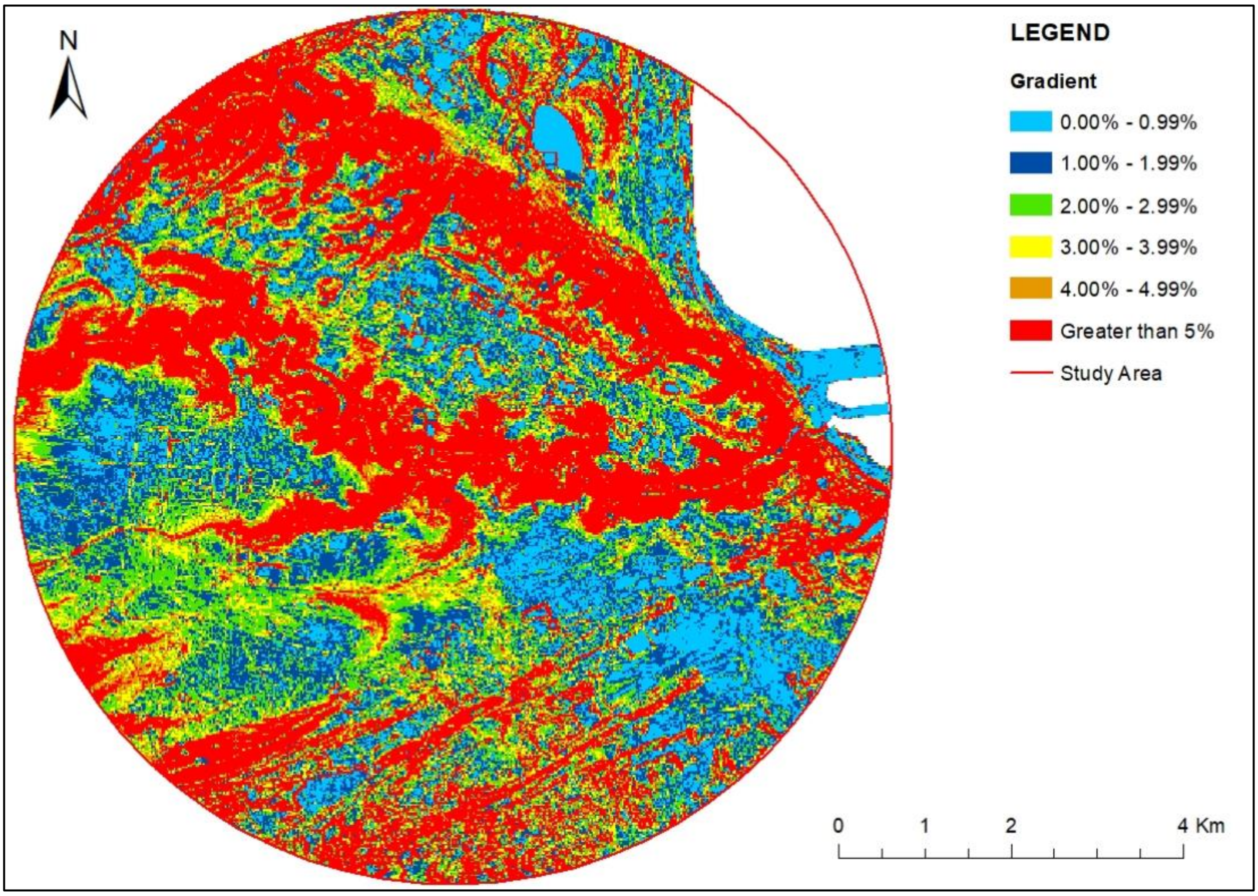


Figure 14: Site Topography within Study Area

Source: Own illustration

4.3 Step 1: Perspective and Associated Qualities

When identifying routes and networks there are often a variety of stakeholders involved with varying perspectives in terms of the qualities they envisage for these. Representatives from affected stakeholders are to meet and agree on the qualities to be included for further investigation. Apart from the perspective of cyclists, other perspectives may include those of technical experts, environmentalists and institutional bodies (e.g. local government). For example, environmental stakeholders will aim to minimise the environmental impact resulting from the construction of any new facilities identified during the planning process. On the other hand, institutions, such as local government, will very often aim to minimise costs as far as possible. Both the aforementioned perspectives are fairly limited in an existing urban setting where the routes are formed combining existing roads and/or paths. It is only during the identification of missing links and routes which deviate from existing cycle infrastructure where they may become more involved. A new link may, for example, be proposed through an environmentally sensitive area, or land which does not belong to the municipality and could be costly to procure. Moreover, deviating from existing infrastructure along a more appropriate route for cyclists may seem wasteful from a government perspective. Greenfield developments, however, differ and will require greater involvement from these stakeholders as various route alternatives are investigated. Irrespective of this, it is the author's opinion that if cycling is to be promoted and adopted as a viable alternative means of transport, it is the user's perspective which is paramount and should be prioritised.

Of the cycle route qualities discussed in Section 2.1.1, directness and coherence are not easily measured spatially using the MCA part of the proposed method. Route directness is later dealt with as Step 5 of the method, where the actual route distance is measured as a ratio of the Euclidean distance to establish whether additional links are required to reduce travel distances and thereby improve user acceptability. Coherence is largely dealt with during the detail design and implementation of routes, where consistency in terms of standards and materials are important. As part of this model, coherence is indirectly dealt with in that the same qualities, criteria and weightings are applied to routes. Moreover, the routes generated by the model are the most direct routes at the lowest "cost" or impedance and follow the existing road network which is intuitive.

As previously noted, cycling takes place for either utility purposes or leisure purposes. To focus on cycling as a daily transport mode, a utility network must be set up as opposed to a recreational network (Deffner, et al., 2012). According to Deffner et al. (2012), in practise utility and recreational networks tend to overlap and should therefore be integrated (Deffner, et al., 2012). For example, many recreational areas are in urban areas among places of work school or shops. At the same time, there is also a demand for utility trips along quiet and attractive routes, parallel to busy roads but at a certain distance from them.

Taking the above into consideration, the case study adopts the perspective of commuter cycling (i.e. utility network) but also includes qualities not considered key for this trip type. As previously noted, if cycling is to be adopted as a viable alternative mode of transport, it needs to cater for all user types as best as practically possible. The proposed method deals with the preference of a utility network in the weighting of route qualities, further discussed in Section 4.5. A change in the weighing of qualities in favour of a leisure network may result in the selection of different routes.

4.4 Step 2: Criteria and Data Identification

Each route quality selected and agreed by stakeholders, as defined in Step 1, can be represented by one or more criterion and each criterion is represented spatially by a map. Criteria will typically be selected by technical experts based on the availability of existing data, and collection of new data where possible and viable.

The criteria used for the case study were based on the availability of geo-spatial information, while still being relevant and applicable to the defined qualities. The criteria and associated datasets used for each quality are summarised in Table 4 below.

Table 4: Criteria and Associated Datasets for each Quality

Quality	Criteria	Dataset
Safety and security	Road class	Existing road network
	Intersection density	Existing road network
	Street lighting	Existing road network
	Urban development	Urban cadastral
Comfort	Gradient	Grid survey
	Intersection density	Existing road network
Attractiveness	Critical biodiversity areas	Critical biodiversity areas
	Recreational areas	NMBM land usage
Environmental conservation	Critical biodiversity areas	Critical biodiversity areas
	Protected areas	Protected areas
	Wetlands	Wetlands

All data used in the model was received from a reputable source, namely the Nelson Mandela Bay local municipality. This data was the latest available at the time of application and was made available for use in various studies, assessments, and designs.

As can be seen from the above table, the same dataset was used for multiple criteria. With the steep costs and time often associated with collecting data, it is imperative that existing data be processed in multiple ways and used where appropriate. Where not a perfect representation, it can be used as a point of departure or proxy, which can be refined as new and more relevant data becomes available. An example of this in the case study is using road hierarchy as a proxy for street lighting, where higher order roads are assumed to be more likely to have good street lighting.

In the SMCA process discussed in Section 4.6.1, criteria are classified either as factors or constraints. Factors can be either a benefit or a cost, depending on how they impact the qualities which they represent. According to ILWIS (2015), a criterion that contributes positively to the output is a benefit and therefore the higher the value, the better it is. A spatial cost contributes negatively to the output and therefore the lower the value, the better it is. Spatial constraints on the other hand are defined as complete no-go areas and these cells are therefore always represented by a zero (ILWIS, 2015). A summary of the various criteria used and their relationship to the respective qualities is provided in Table 5 below.

Table 5: Summary of Perspectives, Qualities and Criteria Considered in Case Study

Perspective	Qualities	Criteria	Relationship of Criteria to Qualities
Commuter Cyclist	Safety and Security	Road Class (Safety)	Spatial cost. The higher the order of the road, the greater the volume of vehicles, number of large trucks, and speeds.
		Intersection Density (Safety)	Spatial cost. The greater the intersection density, the greater the number of potential crossings and points of conflict.
		Street Lighting (Safety and security)	Spatial benefit. The higher the order of the road, the better the street lighting (assumed correlation for case study).
		Urban Development (Security)	Spatial benefit. The presence of development means potentially greater visibility of cyclists.
	Comfort	Gradient	Spatial cost. Steeper gradients are less appealing to commuter cyclists.
		Intersection Density	Spatial cost. The greater the intersection density, the more stopping and starting is required.
	Attractiveness	Critical Biodiversity Areas	Spatial benefit. Route attractiveness increased by passing close by areas of natural beauty.
		Recreational Areas	Spatial benefit. Route attractiveness increased by passing close by areas of natural beauty.
Environmental	Environmental Conservation	Critical Biodiversity Areas	Spatial constraint. Future development may occur but it is not recommended.
		Protected Areas	Spatial constraint. No future development can occur.
		Wetlands	Spatial constraint. No future development can occur.

The datasets identified are vector and raster based. The pre-processing required for each for use in the SMCA is discussed below.

4.4.1 Pre-processing of Vector Dataset

The only vector dataset preserved for use in the study was the existing road network. Ideally, from a cycle network planning perspective, information on the existing path network would add value by providing possible additional links, especially for leisure trip types. As the focus of this study is however on commuter type trips, which according to the LTSA (2004) occur on arterial roads for most of their length, the absence of this information is not deemed serious. Moreover, the purpose of the study is to act as a proof of concept rather than a commissioned real-world application of the method.

The layer of roads is based on information received from the Nelson Mandela Bay Municipality (NMBM). The classification of roads used is that of functional hierarchy (i.e. mobility versus accessibility) and is based on a report generated for the NMBM entitled, “Review Road Access Management” (BKS, 2008). The road classification in the aforementioned report is based on the “National Guidelines for Road Access Management (RAM) in South African”, which is a predecessor of the “South African Road Classification and Access Management Manual” discussed in Section 2.1.3. The classification within the NMBM differs very slightly from the guidelines in terms of the number of road classes and their respective names. A comparison of the two classification systems is provided in Table 6.

Table 6: Comparison between NMBM Classification and South African RAM Guidelines

South African RAM Guidelines		NMBM Class		Function	
No.	Name	No.	Name	Primary	Description
1	Principal arterial (80-120 km/h)	1	Freeway	Mobility	Regional mobility
2-3a	Major arterial / minor arterial (80-90 km/h) (70-80 km/h)	2	Mobility arterial	Mobility	Metropolitan mobility
3b	Activity arterial (50-60 km/h)	3	Activity arterial	Mobility-activity link	Mobility to significant activity nodes/areas within metro
4	Activity street (40-50 km/h)	4	Activity street	Activity	Access to land use in adjacent node or corridor, and limited mobility within the neighbourhood
5	Residential street (40-50 km/h)	5	Residential collector	Activity	Residential collector, providing access to residential areas
	Local street (30-40 km/h)	6	Local street	Activity	Residential street, providing access to individual homes
6	Non-motorised (80m/min)	7	Non-motorised	Activity	Routes for pedestrians and or cyclists

Although the NMBM classification of roads in the above table includes classes 5 to 7, the corresponding map received of the road classes groups these together as streets. The case study therefore uses classes 1 to 4 as per the NMBM classification and streets (in general).

For a vector dataset to be used in the network analysis step, the network topology needs to be in order. This requires that all junctions (nodes) between intersecting roads are defined and that the junctions (nodes) are connected to all sections of road (links) between them. It is also important that any duplicate features (nodes and links) be removed.

The dataset received was of a good quality and did not require any amendments to the topology. The only pre-processing required was to include the functional classification of roads from the "Review Road Access Management" report (BKS, 2008) into the attribute table of the dataset and to clip the road network to within the boundary of the study area.

4.4.2 Pre-processing of Raster Datasets

All of the datasets used were vector datasets, and at the very minimum needed to be rasterised to create a raster map of cells (pixels) to which values could be assigned later in the SMCA process of the method. In the case study, all rasterising of data was done in ArcGIS. A brief description of the pre-processing requirements for each of the raster layers required is provided in Table 7.

Table 7: Summary of Pre-processing of Raster Datasets

Raster Layer	Summary of Process
Road Class	Addition of functional classification discussed in previous section and rasterising.
Intersection Density	Used the Point Density tool in ArcMap on the junctions within the road network to create a continuous surface of intersection (point) density.
Street Lighting	As per road class.
Gradient	Clipped grid survey to study area, imported into Civil Designer 2015 and applied slope shading in intervals of 1% as follows: • 0%-1%; • 1%-2%; • 2%-3%; • 3%-4%; • 4%-5%; • Greater than 5%. Exported layer as a drawing (.dwg) file. Opened polygon layer in ArcGIS, exported it as a shapefile, and thereafter rasterised the shapefile.
Critical Biodiversity Areas	Ready vector data, only needing to be clipped and rasterised.
Protected Areas	Ready vector data, only needing to be clipped and rasterised.
Wetlands	Ready vector data, only needing to be clipped and rasterised.

The software used for the SMCA process requires that all raster layers have the same pixel size. For the case study, a pixel size of 20m x 20m was selected when rasterising the maps. The reasons for this being:

1. The contours used to develop the slope shading for the study area is based on a grid survey of 20m x 20m. The level of accuracy is typically defined by the most course input data and therefore a finer granularity would not result in a more accurate output.

2. An attempt was made to limit the number of intersections per cell to one (1), while maintaining as high a feature spatial accuracy as possible.
3. The pixel size is small enough to aggregate features without losing crucial information.

A screenshot from the model illustrating the road polylines and nodes (or intersections) in relation to the pixel size used is shown in Figure 15.

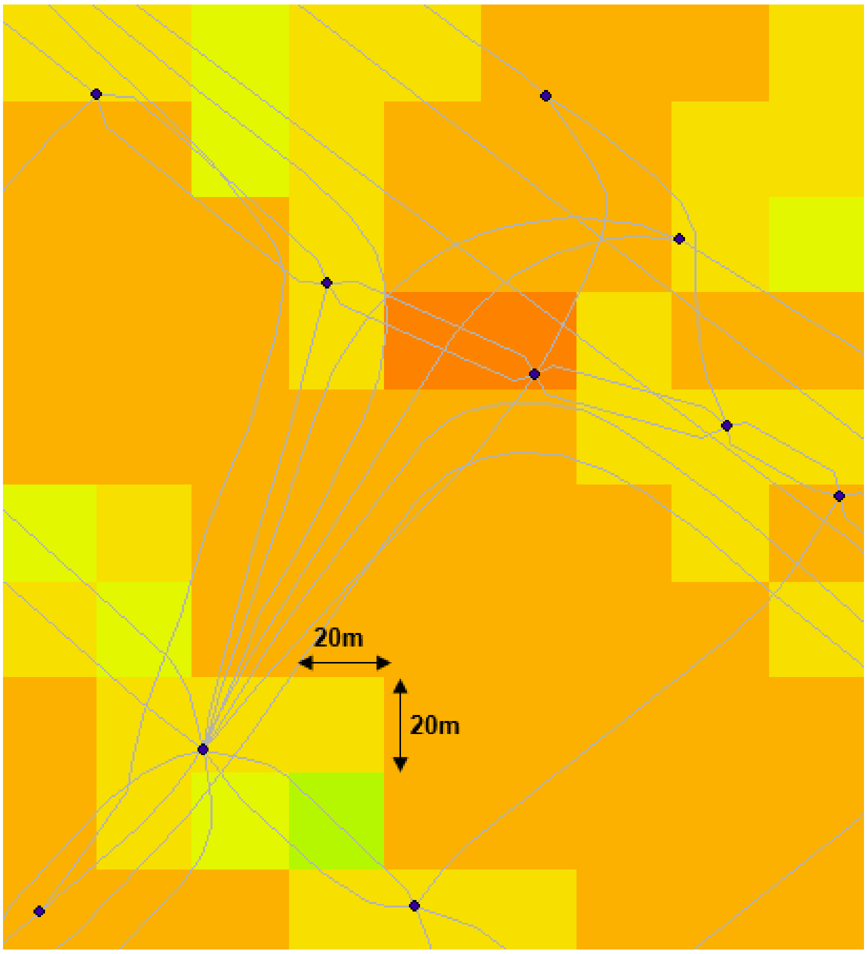


Figure 15: Screenshot of Road Intersections in Relation to Cell Size Used

Source: Own illustration

4.5 Step 3: Weighting of Route Qualities and Criteria

The weighting of route qualities and criteria is an important step in the method and the point at which stakeholders have an influence over the outcome. The spatial nature of the method allows stakeholders to witness the effects of decisions, which assists with buy-in into the process and acceptance of the end results.

In the weight assignment process, there is a distinction between the weighting of criteria and qualities. Furthermore, there is also a distinction between "expert" weights and "policy" weights. Criteria are typically weighted according to objective expert opinion which is often substantiated by scientific knowledge (Keshkamat, et al., 2009). As noted by Keshkamat et al. (2009), the relative importance of criteria can be determined using, for example, magnitude, extent duration and significance of an effect. Qualities are weighted by stakeholders, who need to agree on the weight all qualities under consideration in terms of relative importance.

To assist with the weighting of the cycle route qualities, it is proposed that a hierarchy of qualities key to cycling and based on Maslow's hierarchy of needs, be used as a point of departure, following van Hagen (2015), who did this for public transport in the Netherlands. Figure 16 below provides an adapted illustration of this hierarchy.

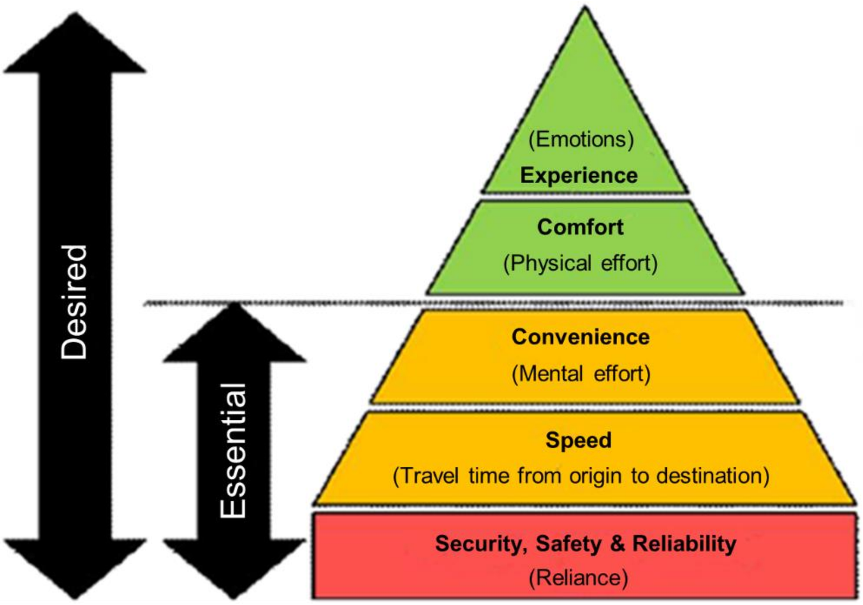


Figure 16: Public Transport Pyramid Illustrating Hierarchy of PT Qualities

Source: Adapted from (van Hagen, 2015)

By substituting the public transport qualities with cycle route qualities, one is able to create a similar pyramid as illustrated in Figure 17 below.

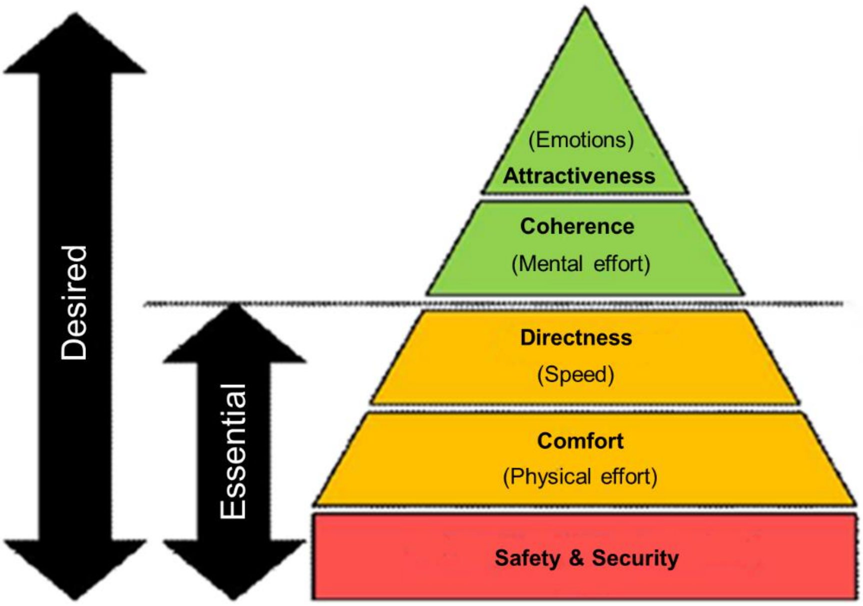


Figure 17: Proposed Hierarchy of Cycle Route Qualities

Source: Own illustration

The hierarchy or ranking of qualities in the above figure is better suited to commuter trips, which is the focus of the case study. The various other cycle trip types under leisure cycling, as noted in Section 2.1.2, may have a different hierarchy depending on their requirements. Moreover, the environment in which the routes are set will also have an impact on the hierarchy and should be taken into account. As noted in Section 4.3, directness and coherence are not easily measured spatially using the proposed method and are dealt with elsewhere in the model. These will therefore not be available for weighting, leaving safety and security, comfort, and attractiveness.

Once the hierarchy of cyclist qualities has been agreed, these need to be ranked in relation to the qualities provided by other stakeholders. Thereafter the qualities are to be weighted by the stakeholders using the ranking as a guide. The sum of the individual weightings is to equal 1 (or 100%).

With regards to the case study in question, as stakeholder engagement was excluded, arbitrary weightings of the qualities were applied in line with the relative importance shown in Figure 17. The exact values used can be found in the following section.

4.6 Step 4: Geo-Spatial Data Processing

4.6.1 Spatial Multi-Criteria Analysis

The SMCA process of the method combines the perspective and associated qualities discussed in Section 4.3, the criteria and geo-spatial datasets from Section 4.4, and the weighting process discussed in Section 4.5.

The software used in this study is ILWIS 3.8.5 (ILWIS, 2015), which is open-source and has a strong SMCA module. In order to perform the analysis, a criteria tree needs to be built in a hierarchical manner, commencing with the perspective (goal), followed by the qualities (sub-goals), and finally factors and constraints, either beneath the qualities or standalone, whichever is applicable. Figure 18 illustrates the criteria tree developed for the case study.

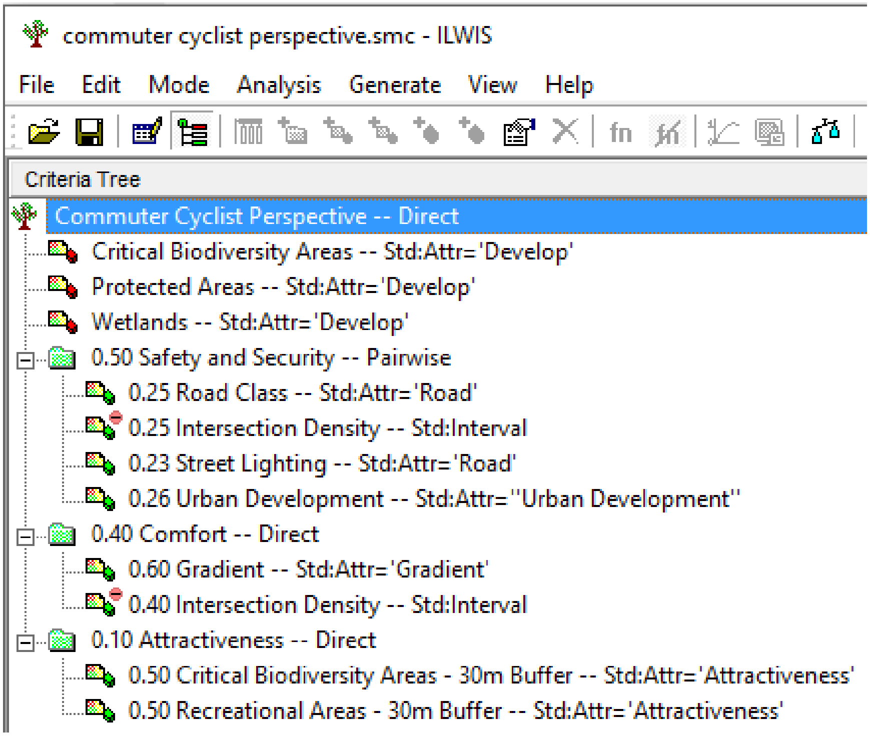


Figure 18: Screenshot of Criteria Tree Developed for Case Study

Source: Own illustration

The weightings applied to the qualities and associated criteria used within the case study, as shown in Table 4, are represented in the above figure as the number preceding each. For example, “0.50 Safety and Security” means that a 50% weighting was applied to the safety and security quality and “0.25 Road Class” means that a 25% weighting was applied to the road class criterion used as a measure of this quality. It worth highlighting that the criteria used for the environmental consideration quality do not have weightings, as these are all constraints and therefore always represent a zero (0) value.

To link raster datasets to criteria, the datasets first need to be imported into ILWIS. Thereafter a common co-ordinate system and geo-reference need to be created. The datasets then need to be resampled using the common geo-reference so that they can be assigned to criteria.

Once the criteria are assigned to the criteria tree and the associated geo-spatial maps linked, a process of standardisation is required. This is necessary as criteria are typically unrelated and have different classifications or units of measure and therefore need to be standardised to utility values between 0 and 1. These values then represent a measure of suitability per pixel for each of the raster maps created for the various criteria. A zero (0) value means that a cell is not suitable for an intended purpose, in this case as a cycle route, whereas a one (1) means that it is highly suitable. Various means of standardisation are available in ILWIS depending on the domain type of the input map (i.e. type of data), which can either be value, Boolean or class. Standardisation according to value can be done using the values on a map or in a column of an attribute table, Boolean assigns utility values depending on whether a pixel is true or false, and class applies utility values based on values in a column of an attribute table. Standardisation according to value (for intersection density) and class (for the remainder of the criteria) were used in the case study. The method applied to each criterion can be found following its name as seen in Figure 18.

With the standardisation of the individual criteria complete, these are then aggregated to create suitability maps per quality, which are in turn used to produce the final suitability map for the perspective under investigation. The cell suitability scores are cumulative meaning that overlapping cells contribute to the final suitability score. The exception to this is where one of the overlapping cells is a constraint, as the resultant scores for these cells will always be 0.

The final suitability map produced from the case study is shown in Figure 19. The colour scale ranges from red to green, which represent not suitable (value “0”) and highly suitable (value “0.9” in this particular case) respectively. Intermediate values are depicted by a range of gradient colours between these two extremes.

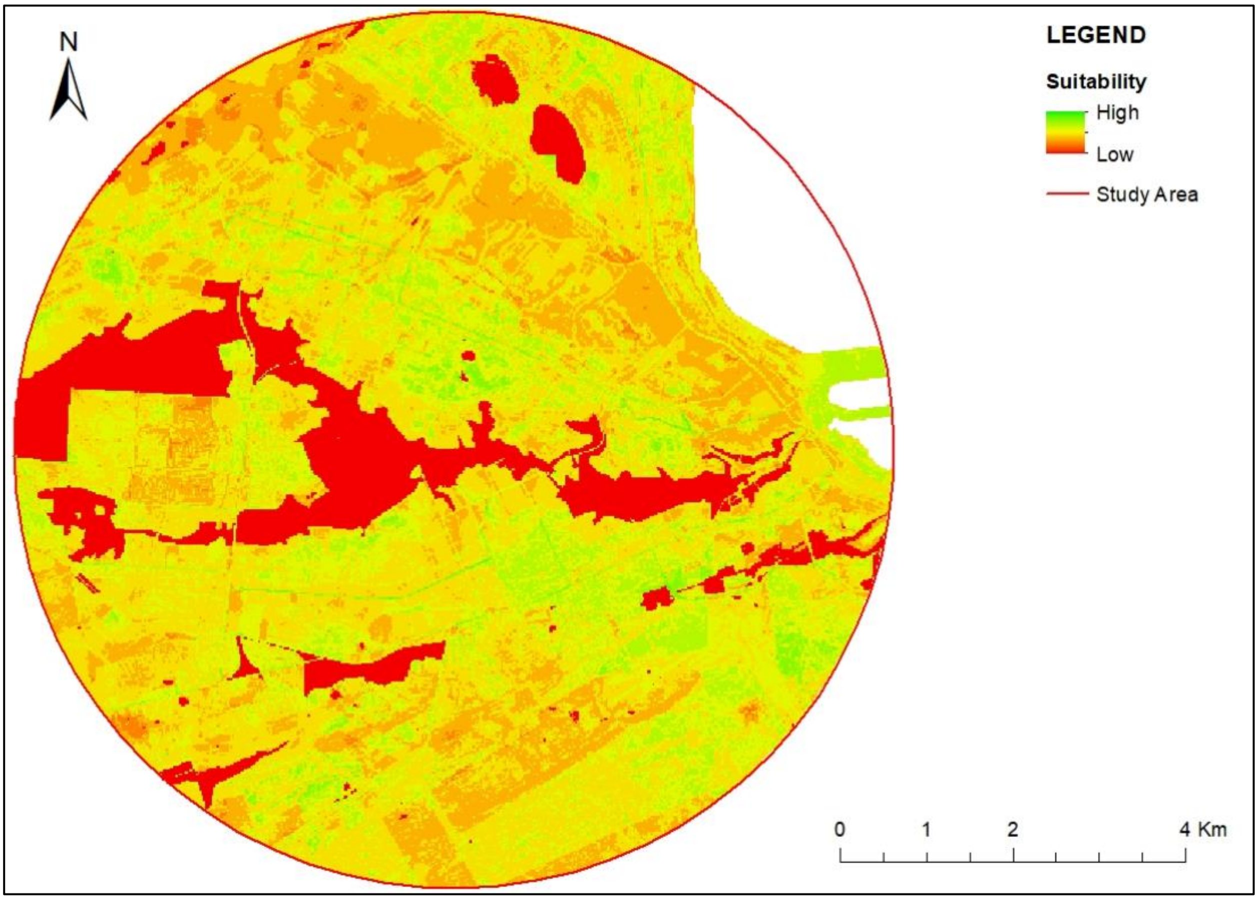


Figure 19: Final Suitability Map for Commuter Cyclist Perspective

Source: Own illustration

The next step of the method involves transferring the suitability values from the above map to the network, and is further discussed in the following section.

4.6.2 Network Analysis

Preparation:

To develop routes, the raster cell scores from a final suitability map are transferred to a road network layer. This can be done using Geospatial Modelling Environment (GME), which is an open-source software package (Beyer, 2015). The algorithm used within the aforementioned software extracts the suitability score from each cell onto the line segment which passes over it. The individual scores are multiplied by the length of the line segment passing over them and summed. This is then divided by the length of the polyline between nodes to produce the Line Weighted Mean (LWM) score for each polyline in the network. The mathematical representation of this is illustrated in Equation 1.

$$LWM = \frac{\sum_{i=1}^{n}(l_i . v_i)}{L} \quad (1)$$

where: l_i = length of line segment "i" — v_i = suitability beneath segment "i"

n = total segments in polyline — L = length of polyline between nodes

The LWM values applied to each polyline then need to be converted to an impedance or “cost” to perform the shortest path analysis in the GIS. This is done in the attribute table of the roads shapefile where the suitability values are inverted by subtracting them from 1 (the maximum suitability) and then multiplying each by the length of the respective polyline to obtain the impedance per polyline between nodes. In the case study ArcMap 10.3.1 (ESRI, 2014) was used but freeware packages such as QGIS may be used instead. The mathematical representation of this is illustrated in Equation 2.

$$\Omega_j = (1 - LWM).L \qquad (2)$$

where: Ω_j = impedance for polyline "j" LWM = line weighted mean

L = length of polyline between nodes

The total impedance per route is calculated by summing the individual polyline impedances forming the route. By multiplying the impedance by the length of a segment between nodes, the total route length continues to play an important role, although not a dominant one. The mathematical representation of this is illustrated in Equation 3.

$$\Omega_R = \sum_{j=1}^{m} \Omega_j \qquad (3)$$

where: Ω_R = total route impedance Ω_j = impedance for polyline "j"

m = total number of polylines forming route

This final metric can be used when comparing alterative routings between a common O-D pair. For example, when comparing a route developed by the shortest path analysis to either an existing or pre-defined route (refer to Section 4.8). The higher the Ω_R value the greater the impedance or “cost”.

Building the Network:

To use the Network Analyst functionality in ArcMap, a network dataset needs to be built using the road shapefile which contains the impedance values. In the network dataset setup wizard, the turns, connectivity and elevation settings can remain at default. Thereafter attributes of the various perspectives considered are to be added and named accordingly. The usage type is to be defined as “cost” and the data type as “double”. Using the “Evaluators” button, the source values are to be selected as type “Field” and the “Value” is to be set as the impedance column in the road shapefile for each perspective. Once complete the network dataset is ready for determining the shortest routes at the lowest cost or impedance.

In the case study, the attribute added was for the perspective of the commuter cyclist and the corresponding evaluator value was set to the field in the road shapefile containing the impedance values for each road segment in the network. Figure 20 shows the completed “Evaluators” window in ArcMap.

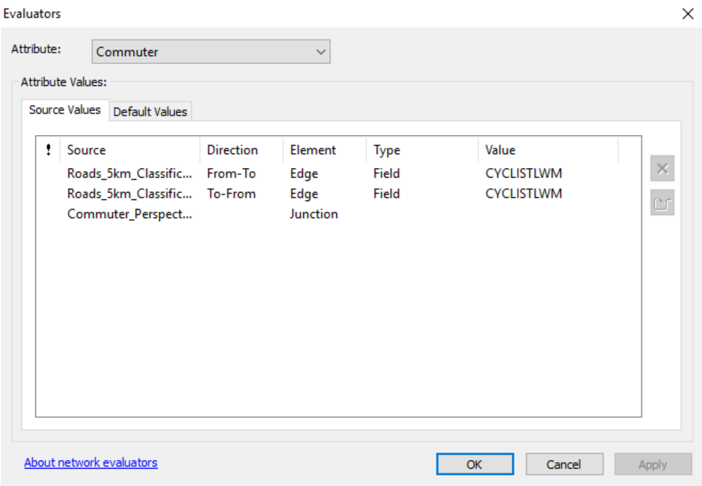


Figure 20: Completed Evaluators Window in ArcMap for Case Study

Source: Own illustration

Solving the Network:

With the impedance values assigned to the road network, it is then possible to solve either individual routes or a network of routes between defined O-D pairs using the Network Analyst extension in ArcMap. An individual route created between two neighbourhoods in the case study area, namely Charlo and Newton Park, is illustrated in Figure 21 below.

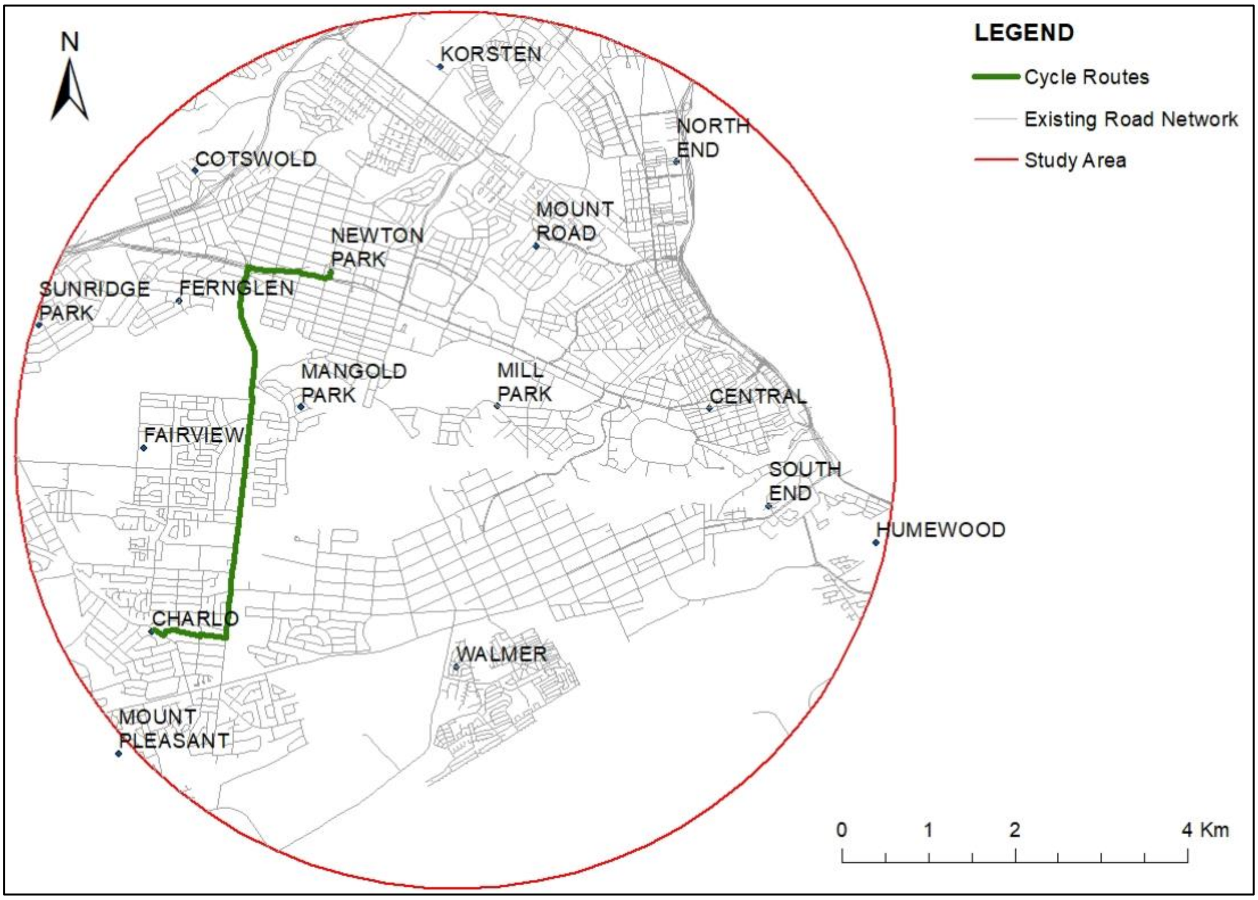


Figure 21: Optimal Cycle Route between Charlo and Newton Park

Source: Own illustration

Figure 22 illustrates the route network generated between all the neighbourhood centroids contained within the study area.

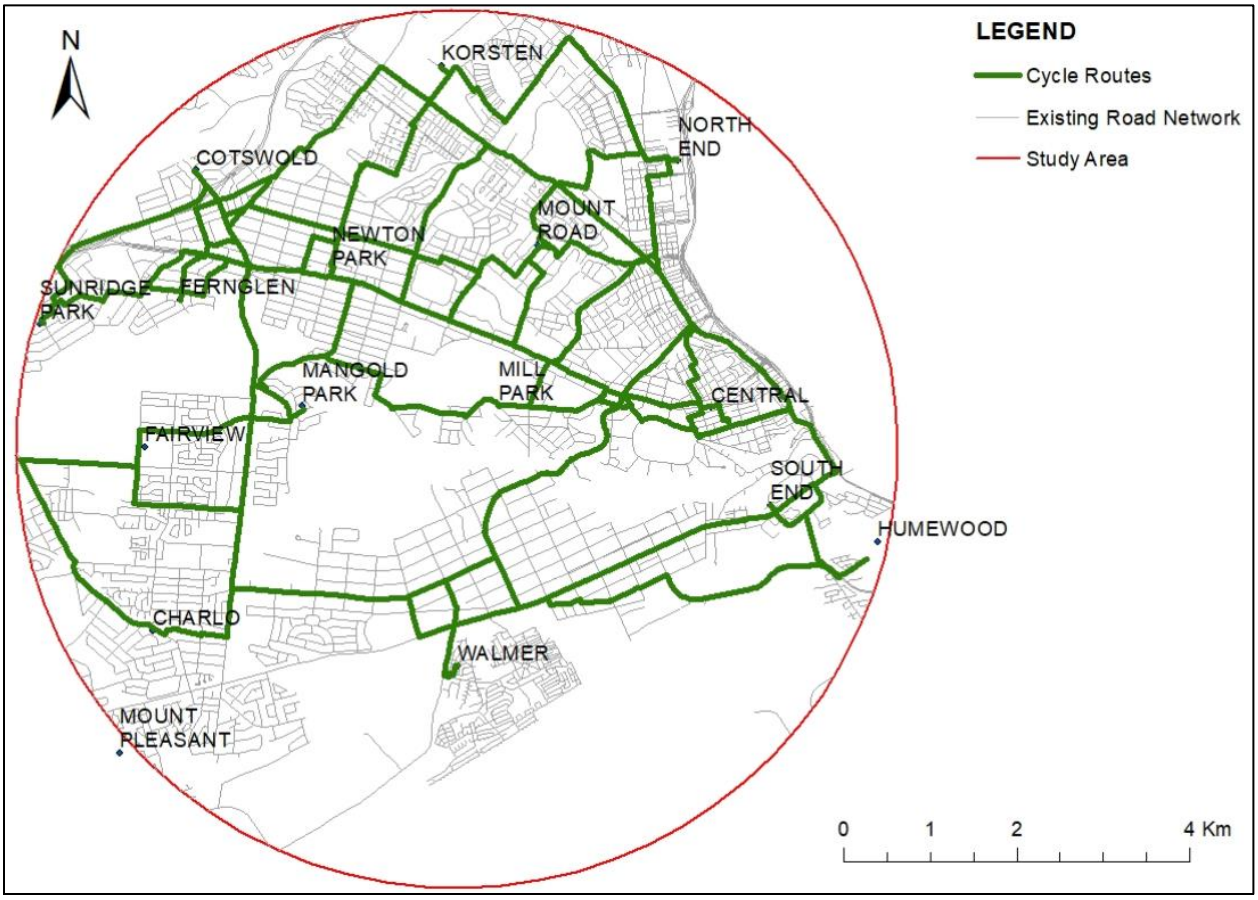


Figure 22: Developed Cycle Route Network According to Commuter Cycle Perspective

Source: Own illustration

4.7 Step 5: Cycling Route Directness

Cycle route directness (CRD) is a ratio of the actual route distance versus the straight line or Euclidean distance between two points. A ratio of one (1) is the best possible and occurs where the Euclidean and route distances are the same. The mathematical representation of this is illustrated in Equation 4.

$$CRD = \frac{L_R}{L_S} \quad (4)$$

where: CRD = cycle route directness

L_R = actual route length $\quad$ L_S = Euclidean distance

According to Dill (2004), the “INDEX PlanBuilder Users Guide” developed by Criterion Planners Engineers recommends pedestrian route directness (PRD) ratios of 1.2 to 1.5, with values of 1.6 to 1.8

being considered as indirect. A large factor influencing PRDs is the layout of neighbourhoods. Randall and Baetz (2001) found that neighbourhoods with grid street patterns and relatively short blocks had PRDs of 1.4 to 1.5 whereas those with curvilinear streets and cul-de-sacs had PRDs between 1.63 and 1.88. As similar guidelines were not found for CRD in the literature review done as part of this study, the PRD thresholds have been adopted until further research has been conducted in this field for cycling. PRDs and CRDs are therefore assumed to be interchangeable.

In the case study, the CRD calculated for the route illustrated in Figure 21 is 1.35, which implies that the route directness is acceptable. Table 8 below summarises the characteristics of this route.

Table 8: Characteristics of Route Developed

Description	Value
Route length	6,305 m
Euclidean distance	4,666 m
CRD	1.35

The same approach applied to a single route can be also be applied at a network level. Table 9, in the form of an O-D matrix, contains the CRD values between all O-D pairs for the network illustrated in Figure 22.

Table 9: O-D Matrix Containing CRD Ratios between All O-D Pairs

O / D	CENTRAL	CHARLO	COTSWLD	FAIRVIEW	FRNGLN	HUMEWOOD	KORSTEN	MNGLD PRK	MIL PRK	MNT RD	NWTN PRK	NORTH END	SOUTH END	SUNRIDGE	WALMER
CENTRAL	0.00	1.28	1.07	1.29	1.10	1.65	1.17	1.49	1.09	1.41	1.04	1.28	2.30	1.12	1.52
CHARLO	1.28	0.00	1.22	1.97	1.67	1.16	1.29	1.33	1.58	1.40	1.35	1.35	1.17	2.19	1.49
COTSWLD	1.07	1.22	0.00	1.42	1.31	1.23	1.36	1.16	1.33	1.19	1.17	1.33	1.30	1.27	1.38
FAIRVIEW	1.29	1.97	1.42	0.00	2.56	1.31	1.36	1.18	1.36	1.35	1.46	1.40	1.36	3.41	1.51
FRNGLN	1.10	1.67	1.31	2.56	0.00	1.28	1.30	1.79	1.48	1.26	1.21	1.37	1.37	1.30	1.65
HUMEWOOD	1.65	1.16	1.23	1.31	1.28	0.00	1.22	1.61	1.42	1.52	1.26	1.38	1.36	1.28	1.22
KORSTEN	1.17	1.29	1.36	1.36	1.30	1.22	0.00	1.57	1.58	1.46	1.21	1.53	1.27	1.28	1.63
MNGLD PRK	1.49	1.33	1.16	1.18	1.79	1.61	1.57	0.00	1.84	1.66	1.80	1.61	1.77	1.64	1.87
MIL PRK	1.09	1.58	1.33	1.36	1.48	1.42	1.58	1.84	0.00	1.44	1.50	1.22	1.66	1.42	2.06
MNT RD	1.41	1.40	1.19	1.35	1.26	1.52	1.46	1.66	1.44	0.00	1.36	1.60	1.71	1.23	1.56
NWTN PRK	1.04	1.35	1.17	1.46	1.21	1.26	1.21	1.80	1.50	1.36	0.00	1.46	1.37	1.18	1.81
NORTH END	1.28	1.35	1.33	1.40	1.37	1.38	1.53	1.61	1.22	1.60	1.46	0.00	1.42	1.32	1.33
SOUTH END	2.30	1.17	1.30	1.36	1.37	1.36	1.27	1.77	1.66	1.71	1.37	1.42	0.00	1.35	1.21
SUNRIDGE	1.12	2.19	1.27	3.41	1.30	1.28	1.28	1.64	1.42	1.23	1.18	1.32	1.35	0.00	1.71
WALMER	1.52	1.49	1.38	1.51	1.65	1.22	1.63	1.87	2.06	1.56	1.81	1.33	1.21	1.71	0.00

As with any matrix, the values in Table 9 are mirrored either side of the diagonal line which represents intra-zonal travel (i.e. same origin and destination). The cells highlighted in red with red text represent ratios in excess of 1.6 and are therefore defined as indirect. Of the 105 O-D links, 24 exceed 1.6, resulting in 22.9% of the network links being indirect. The majority of these occur due to the Baakens River Valley, which cuts through the study area, thereby limiting the number of crossing points. In order to reduce these, additional links across the valley are required. The average CRD value for the network works out to 1.45, which implies that the overall network can be considered as direct. This value should, however, be treated with care and more attention should be given to the individual routes and the percentage of those which are indirect as discussed earlier.

To illustrate the benefits of adding a link, even a relatively minor one, a link was added between one of the five (5) main crossings of the Baakens River Valley and a local street as illustrated in Figure 23.

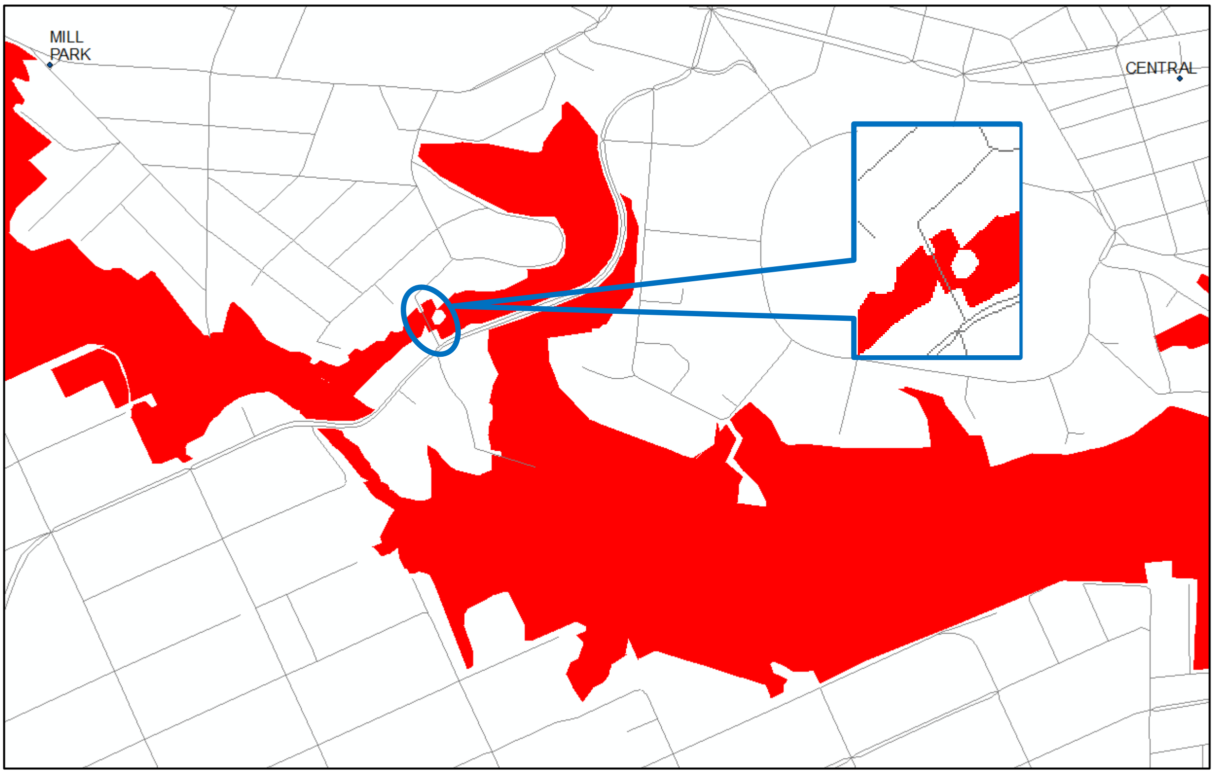
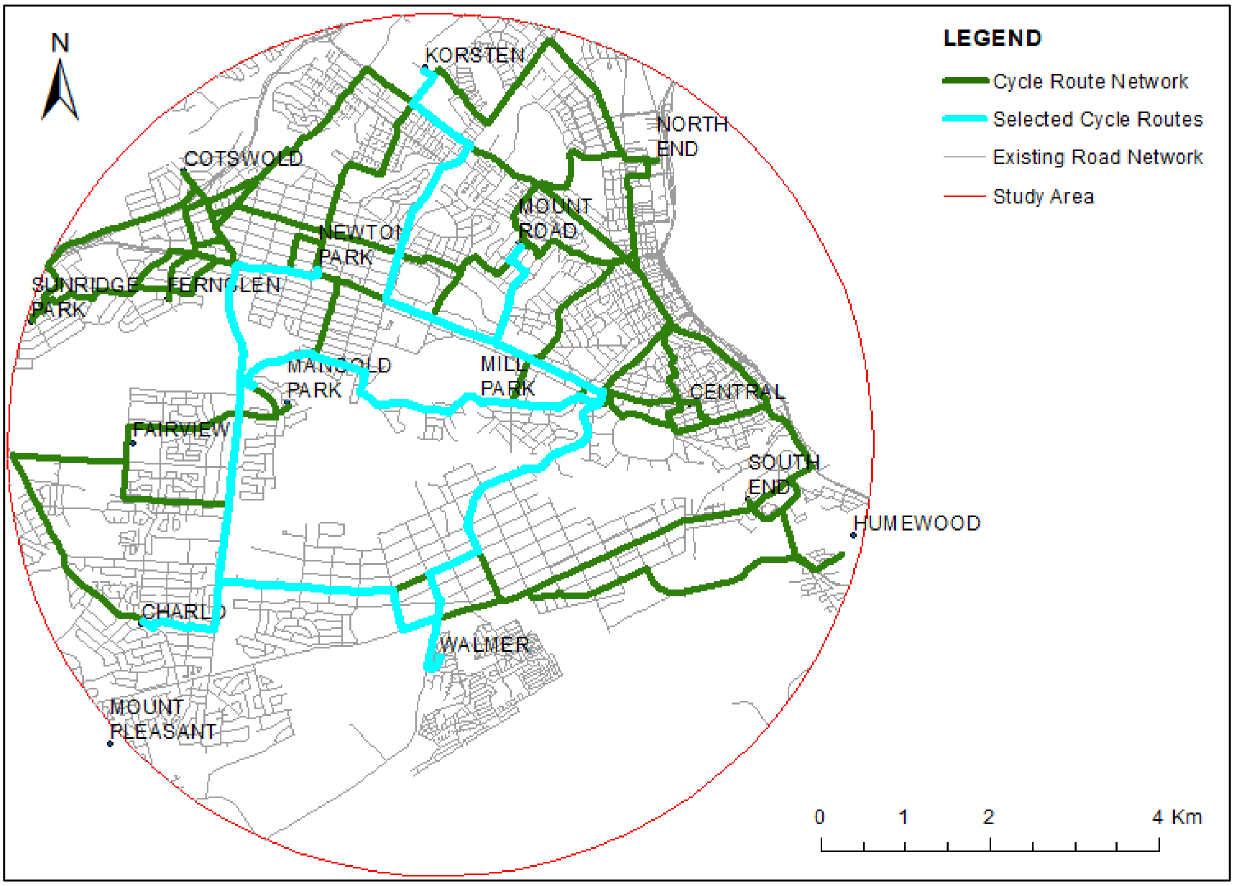


Figure 23: Additional Link Added to Network to Reduce CRD Values

Source: Own illustration

A comparison of the original routing according to the base network, and the revised routing as a result of the additional network link is shown in Figure 24. The routes affected by the addition of the link are:

- Walmer to Mount Road;
- Walmer to Korsten;
- Walmer to Mill Park;
- Walmer to Newton Park; and
- Charlo to Mill Park.



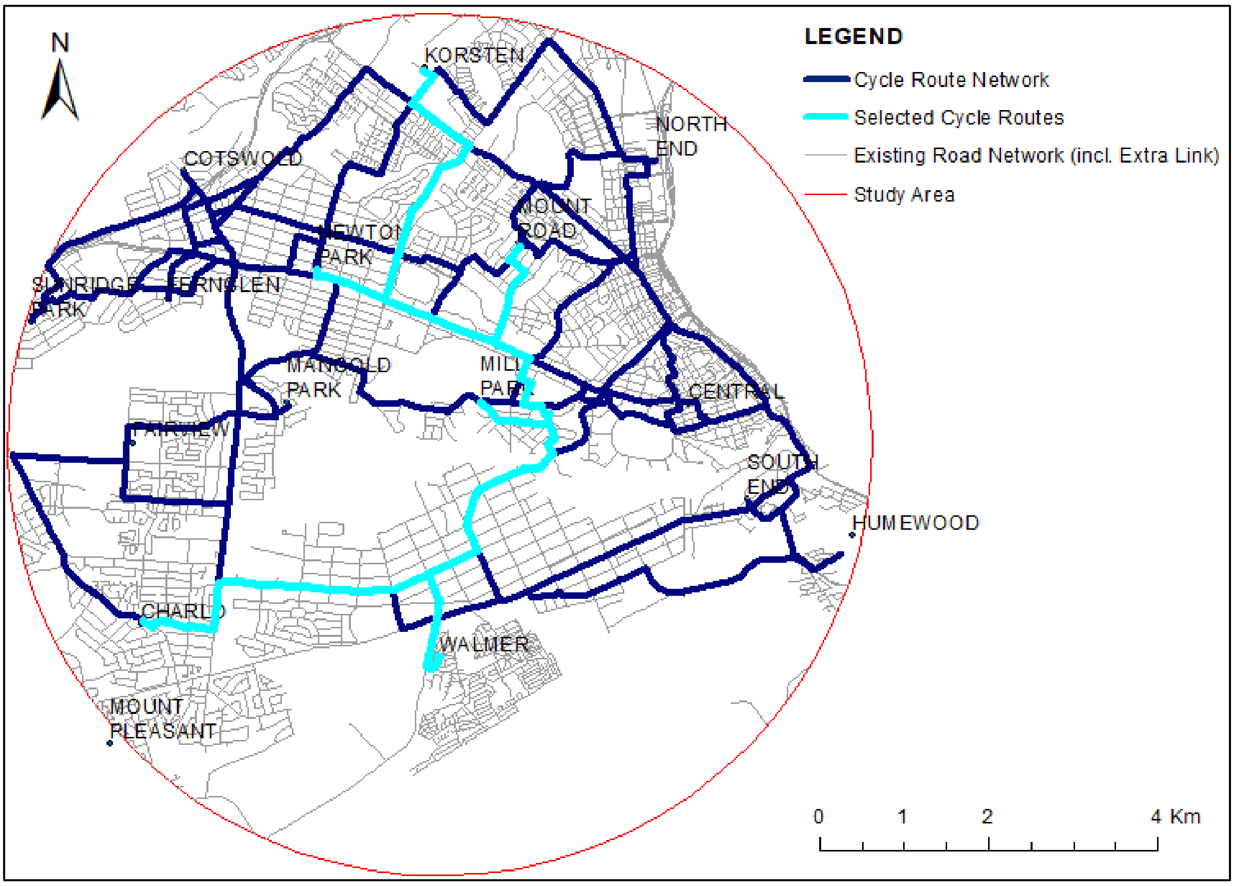


Figure 24: Comparison of Original (top) and Amended (bottom) Routings due to Additional Network Link

Source: Own illustration

To observe the effect of the additional link on the CRD values, a new matrix using the revised route lengths was developed as illustrated in Table 10. Of the five (5) routes affected, four (4) showed a reduction in the CRD values and one (1) a slight increase (refer to cells with red boarders in below table). Of the four reductions, only the route between Walmer and Korsten was reduced below the threshold of 1.6 to be considered as direct. The CRD which increased slightly was for the route between Charlo and Mill Park. The reason for this is due to the heavy weighting applied to safety and security. Although the optimal route is shorter in the original network, it is considered more dangerous as it passes by vacant pieces of land and on higher order roads for a greater portion of its length. The route lengths of the original routing and revised routing are 7,565m and 7,730m respectively, a difference of 165m. The impedance values of the original routing and revised routing are 4,017 and 3,466 respectively, a difference of 551. The greater impedance of the original routing, compared to the difference in route length, resulted in the shift of the optimal route in the revised routing.

The average CRD for the revised network is once again 1.45 and 22.9% of the network links can again be classified as indirect. At a network level nothing has therefore changed.

It is important to note that although the optimal routing, of the affected routes, according to the model changed after the addition of the link, the roads identified for routes are unchanged in the case study. Cyclists therefore have the option to select the route they feel most comfortable using.

Table 10: O-D Matrix Containing CRD Ratios between All O-D Pairs of the Revised Network

O / D	CENTRAL	CHARLO	COTSWLD	FAIRVIEW	FRNGLN	HUMEWOOD	KORSTEN	MNGLD PRK	MIL PRK	MNT RD	NWTN PRK	NORTH END	SOUTH END	SUNRIDGE	WALMER
CENTRAL	0.00	1.28	1.07	1.29	1.10	1.65	1.17	1.49	1.09	1.41	1.04	1.28	2.30	1.12	1.52
CHARLO	1.28	0.00	1.22	1.97	1.67	1.16	1.29	1.33	1.61	1.40	1.35	1.35	1.17	2.19	1.49
COTSWLD	1.07	1.22	0.00	1.42	1.31	1.23	1.36	1.16	1.33	1.19	1.17	1.33	1.30	1.27	1.38
FAIRVIEW	1.29	1.97	1.42	0.00	2.56	1.31	1.36	1.18	1.36	1.35	1.46	1.40	1.36	3.41	1.51
FRNGLN	1.10	1.67	1.31	2.56	0.00	1.28	1.30	1.79	1.48	1.26	1.21	1.37	1.37	1.30	1.66
HUMEWOOD	1.65	1.16	1.23	1.31	1.28	0.00	1.22	1.62	1.42	1.52	1.27	1.38	1.36	1.28	1.22
KORSTEN	1.17	1.29	1.36	1.36	1.30	1.22	0.00	1.57	1.58	1.46	1.21	1.53	1.27	1.28	1.56
MNGLD PRK	1.49	1.33	1.16	1.18	1.79	1.62	1.57	0.00	1.84	1.66	1.80	1.61	1.77	1.64	1.87
MIL PRK	1.09	1.61	1.33	1.36	1.48	1.42	1.58	1.84	0.00	1.44	1.50	1.22	1.66	1.42	1.69
MNT RD	1.41	1.40	1.19	1.35	1.26	1.52	1.46	1.66	1.44	0.00	1.36	1.60	1.71	1.23	1.47
NWTN PRK	1.04	1.35	1.17	1.46	1.21	1.27	1.21	1.80	1.50	1.36	0.00	1.46	1.37	1.18	1.72
NORTH END	1.28	1.35	1.33	1.40	1.37	1.38	1.53	1.61	1.22	1.60	1.46	0.00	1.42	1.32	1.33
SOUTH END	2.30	1.17	1.30	1.36	1.37	1.36	1.27	1.77	1.66	1.71	1.37	1.42	0.00	1.35	1.21
SUNRIDGE	1.12	2.19	1.27	3.41	1.30	1.28	1.28	1.64	1.42	1.23	1.18	1.32	1.35	0.00	1.71
WALMER	1.52	1.49	1.38	1.51	1.66	1.22	1.56	1.87	1.69	1.47	1.72	1.33	1.21	1.71	0.00

4.8 Comparison of Route Alternatives

For the purpose of the case study, an alternative route was selected between the suburbs of Charlo and Newton Park, and compared to the optimal route developed by the proposed method. The alternative route, which also happens to be the shortest in terms of distance, is shown in Figure 25. The optimal route between this O-D pair was shown earlier and can be found in Figure 21,

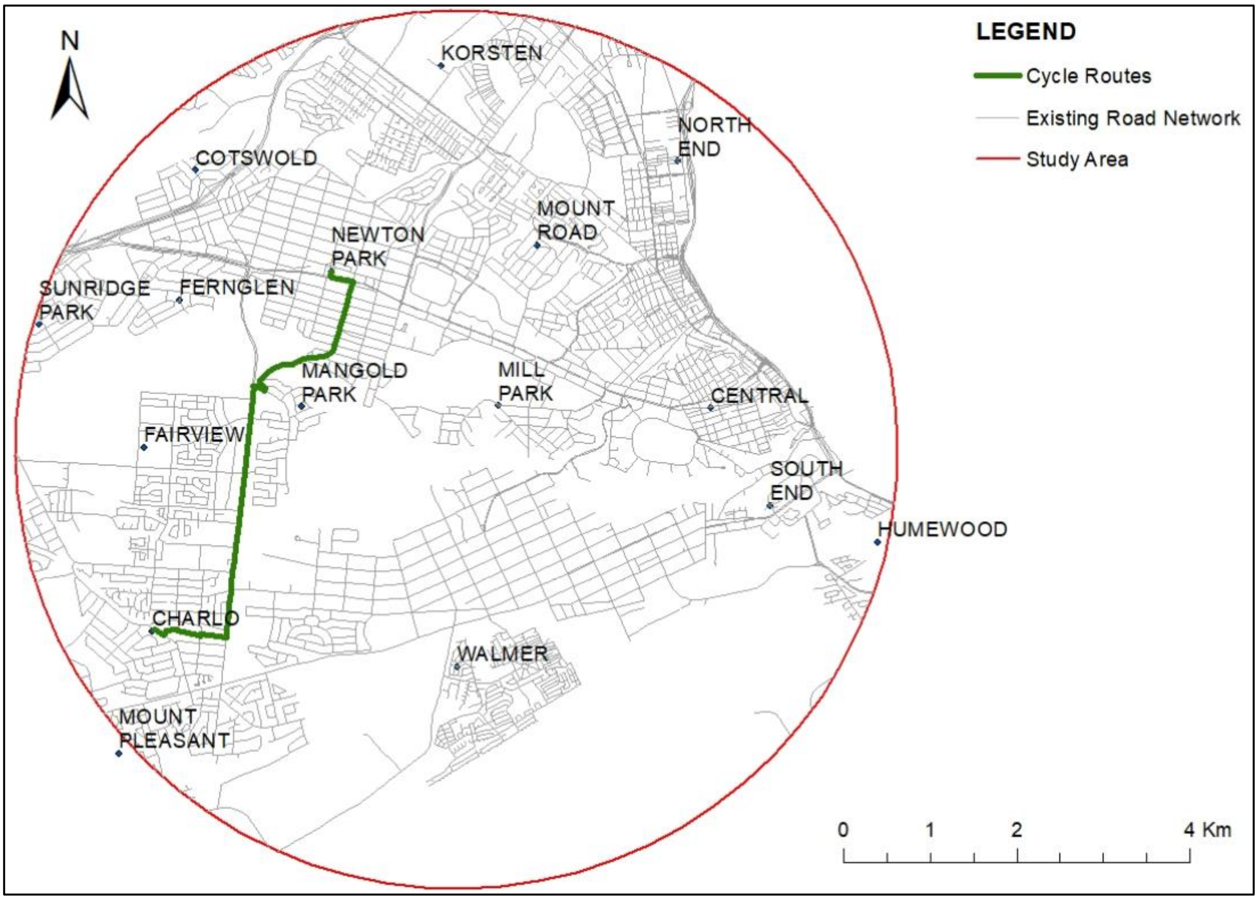


Figure 25: Alternative Route between Charlo and Newton Park

Source: Own illustration

A comparative analysis of the resultant parameters in terms of total route impedance and total route length can be found in Table 11.

Table 11: Comparison of Total Route Impedance and Length for Optimal and Alternative Routes

Route	Total Impedance	Total Length (m)
Optimal	3,105	6,305
Alternative	3,148	6,261

4.9 Sensitivity analysis

Typically, a sensitivity analysis is required given potential uncertainty surrounding the validity of the inputs, particularly the weighting of qualities and criteria. Alternatives where amendments to these are made provides a means for examining the extent to which vagueness affects the final overall results and in so doing helps to resolve disagreements between stakeholders. As the case study is a proof of concept and not a commissioned real-world application of the proposed method with stakeholders, it was decided that a sensitivity analysis was not required.

5 Conclusions and Recommendations

5.1 Conclusions

The study set out to develop an objective method for the development and evaluation of cycle route networks, at a strategic level, as its primary aim. To achieve this, the principles set out in the "Cycle Network and Route Planning Guide" (Land Transport Safety Authority, 2004) together with the method developed Keshkamat (2007) were used as the core of the proposed method. The theoretical case study undertaken proves that the main aim was achieved as the objectives set out in Section 1.5 were reached. To summarise how the objectives were met, the route qualities required by cyclists for a specific trip type (i.e. commuter cycling), where identified and combined with the route qualities required by other stakeholders, which in the case study was environmental considerations. Suitable criteria to measure the required qualities, including criteria which could be used as a proxy in the absence of the required data, then underwent a SMCA process to determine suitability values for all road segments within the road network. Lastly, optimal routes were developed between O-D pairs using a network analysis tool in GIS, which calculates the impedance values of all possible route alternatives between O-D pairs, using the suitability values, and selects the routes with the lowest impedance between each.

The requirements of the method developed as set out in Section 1.6 were also mostly met. Stakeholder engagement is facilitated as stakeholders are involved in the selection and weighting of route qualities, they are able to view and comment on the criteria and suitability maps created, and they are able to take part in the identification of any missing or required links in a network. The method is universal and adaptable as it can include a variety of criteria (both spatial and non-spatial) from numerous stakeholders, and not just cyclists. As for satisfying the requirements of being transparent and back-traceable, transparency is achieved through the aforementioned stakeholder engagement, and the optimal routes selected can be traced back to the selection and weighting of route qualities and the resulting criteria and suitability maps produced. The requirements not completely met are that it needs to be uncomplicated and user-friendly, and that it must be cost-effective and time efficient. A fair level of skill is required to set the model up, however, it is fairly easy to use and amend thereafter. The cost and time to collect geo-spatial data can also be extensive if not readily available.

Of the cycle network approaches discussed in Section 2.1.4, the proposed method uses a combination of both the "roads or paths" and "needs" approaches. This is done by imposing the route qualities applicable to cyclists and other stakeholders onto a road and / or path network so that routes which best satisfy the requirements of all stakeholders are identified.

In addition to successfully developing routes between defined O-D pairs, the proposed method provides a mechanism to evaluate route options using the impedance score per route. This is similar to the needs assessment method noted in Section 2.2.5 which evaluates routes against their ability to meet cyclists needs. Where it differs is that the impedance scores are qualitative and therefore allow for an objective comparison of routes which is advantageous as it facilitates stakeholder buy-in. The limitation is that unlike the needs assessment which can assess the extent to which routes satisfy all trip types, using the impedance scores only allows the routes to be compared in line with the perspective under consideration (e.g. commuter cycling versus recreation cycling).

The proposed method also provides an additional criterion for consideration in the prioritisation of routes. The route directness or circuity as measured by the CRD can be used with more indirect routes (i.e. higher CRD values in excess of 1.6) receiving a higher priority. It is suggested that this criterion not be used in isolation but be combined with other criteria such as demand, crash data and project costs for example. It must be emphasised here that the CRD measure was adopted from pedestrian route directness with a direct correlation, as a comparative measure for cycling could not be found in the literature review undertaken. The author therefore recommends that there be greater research into the appropriateness of the threshold value between direct and indirect routes for cycling.

The proposed method advances geo-spatial modelling techniques and improves on existing methods as it is capable of considering the cycle route qualities required by numerous stakeholders (focused around the needs of cyclists), while still taking route length into consideration in the selection of optimal routes. Typically, existing methods apply either a pre- or post-evaluation of route alternatives using either supply- or demand-based criteria to select the best alternative. The proposed method improves on this by using both supply- and demand-based criteria (as with the Supply- and Demand-Based Method discussed in Section 2.3.4) to ultimately assign impedance values per road or path segment, which are later used in the network analysis to define the optimal routes of lowest cost between O-D pairs. The length of the route is controlled in that the impedance per segment is calculated by using the length of a segment as a multiplier, and therefore “total route length” continues to play an important role, although not a dominant one.

The proposed method, being strategic in nature, still requires further investigation and infrastructure improvements to ensure the route qualities are met. For example, lower order roads with less heavy vehicles and lower speeds may be preferable to leisure cyclists but if a cycle lane or path is not provided, the route may be unusable. Similarly, although intersection type may be included as a criterion (in a limited manner as it only affects a small road segment and therefore may not have a big influence on route determination), how the intersection is crossed will very often require further design (i.e. cycle boxes, lanes through intersections, etc).

Where the current study falls short is that due to time and resource constraints, an accurate O-D matrix could not be generated and stakeholders were not engaged in the development and evaluation of route alternatives. Although the author is of the opinion that this does not compromise the method in terms of developing a cycle route network, a real-life application of the method as part of the full planning process will confirm the suitability of the method and provide feedback on its ease of use.

With particular reference to the case study, it is interesting to note that even a relatively minor link can affect multiple routes and have a substantial influence on the usability of the network. This is however only possible if the link both reduces impedances and travel distances.

Lastly, although founded on the method developed by Keshkamat (2007), this study adds innovation to the field of SMCA by: (1) solving for a network of routes as opposed to a single route; (2) proposing a relative weighting of route qualities adopted from the qualities key to successful public transport developed by the Dutch Railway company and which can be used as a point of departure between stakeholders; and (3) suggesting a method of measuring route directness or circuity using CRD that can be used in the prioritisation of cycle facility upgrades.

5.2 Recommendations

Based on the conclusions and findings during the research, the following recommendations can be made:

- To showcase the proposed method and validate its suitability in determining and evaluating cycle route networks, it is recommended that the proposed method be used as part of the full planning process discussed in Section 2.2. This includes assessing cycle demand, identifying the bicycle route network (this being the focus of the proposed method), evaluation of route alternatives (using the impedance scores used to derive the routes), and prioritisation of infrastructure requirements (by considering the CRD value calculated for each route as one of the criteria).
- One of the objectives noted in Section 1.5 was to identify how readily available data can be used as a proxy for criteria where the required data is not available. It is recommended that there be further research into the relationships between criteria and data, and the pre-processing required to get it into the correct format. A guideline document detailing how data can be used as a proxy where information is missing is then to be drawn up to assist planners in the development of the model.
- The cycle route directness (CRD) measure used in this study was adopted from pedestrian route directness (PRD) with a direct correlation, as a comparative measure for cycling could not be found in

the literature review undertaken. It is therefore recommended that further research in this field be undertaken to confirm the threshold value between direct and indirect routes for cycling.

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Appendix

Ethics Form

EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zakiya Chikte (**Zakiya.chikte@uct.ac.za**); New EBE Building, Ph 021 650 5739). Students must include a copy of the completed form with the dissertation/thesis when it is submitted for examination.

Name of Principal Researcher/Student: Michael Vorster **Department: Civil Engineering**

If a Student: **Degree: M.Eng.** **Supervisor: Zuidgeest**

If a Research Contract indicate source of funding/sponsorship: N/A

Research Project Title: Approach to Cycle Route Network Determination, within the South African Context, using Spatial Multiple Criteria Evaluation and Shortest Path in GIS

Overview of ethics issues in your research project: Note: incorrect answer crossed out

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	~~YES~~	NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	~~YES~~	NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	~~YES~~	NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	~~YES~~	NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	[signature] James Michael Vorster	30/11/2015

This application is approved by:

Supervisor (if applicable):	[signature] Zuidgeest	30/11/2015
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.	[signature] R. BEHRENS	01 NOV 2015
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		