CYCLE ROUTE NETWORK DEVELOPMENT AND EVALUATION USING SPATIAL MULTI-CRITERIA ANALYSIS AND SHORTEST PATH ANALYSIS

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ABSTRACT

Cities today face many urban challenges and sustainable transportation is one of these. Cycling has been proposed as one of a basket of solutions as it is an efficient way of travelling in urban areas over short to medium distances for a variety of trip types. The planning of cycle route networks is, however, challenging as traditional methods are incapable of adequately dealing with the conflicting objectives of various stakeholders and multiple spatial and non-spatial criteria used to measure these. Because of this, traditional methods are criticised for not being open and transparent, leaving many stakeholders dissatisfied. Moreover, the route qualities desired by cyclists are rarely adequately included in the identification of optimal routes. To address these concerns, the proposed method takes advantage of spatial multi-criteria analysis (SMCA), which combines 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 paper uses SMCA to develop a network of optimal cycle 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 quantitative scores assigned to routes allows for a subjective evaluation of alternatives, and the directness of routes calculated in the final step of the method can be used as an additional metric in the prioritisation of planned infrastructure upgrades. The case study showcases the method’s ability to act as a decision support system for cycle route network planning at a strategic level.

1. INTRODUCTION

Active mobility in the form of walking and cycling have been suggested as one means to address urban transport challenges as it simultaneously promotes sustainability and improves the liveability of cities.

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

To address the above requirements, the proposed method aims to develop an objective geo-spatial tool for the planning of cycle routes and networks, which takes cognisance primarily of the requirements of cyclists as the end users, but also the perspectives of other stakeholders. Planners will be able to take advantage of the graphical interface and quantitative results available through the use of GIS, to objectively select optimal routes between origin-destination (O-D) pairs, and ultimately develop a cohesive network.

For the method to gain acceptability amongst stakeholders and practitioners, the following requirements are essential: (1) it must facilitate stakeholder engagement; (2) it needs to be universal and adaptable to address multiple criteria from various stakeholders; (3) it must be uncomplicated, transparent and back-traceable; and (4) 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: (5) capable of developing either a single route or a network of routes, depending on the requirements of the study; and (6) flexible in its use of available data sources as a proxy for criteria where the required data is not available.

To showcase the method, a case study within a defined area in the metropolitan of Port Elizabeth in South Africa is provided.

2. PLANNING A CYCLE NETWORK

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. 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.

To create a cycling inclusive environment, for both experienced and novice users, cycle routes should exhibit the following qualities (Land Transport Safety Authority, 2004) and (National Department of Transport, 2014):

- **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 their surroundings, enhancing their security and looking attractive.

The core required route qualities noted above and relative importance of each, particularly for experienced cyclists, vary depending on the trip purpose and more specifically type. It is important to note, however, that apart from experience level, the age and/or gender of cyclists influences the required route qualities and relative importance thereof. Moreover, local conditions may also influence the specific route requirements and need to be taken into consideration. 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.

The method presented in this paper aims to provide a tool to identify optimal routes by qualitatively evaluating all possible route alternatives along the existing road and/or cycle path network against the route qualities defined and weighted by stakeholders. Moreover, where the deviation of a resulting route is calculated to be indirect, alternative links may be added and evaluated. This is achieved as the 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).

Given the data requirements for a comprehensive assessment of route alternatives, especially at a network level, and the likelihood that the data will not be readily available, the method is best suited at a strategic level of planning. As such, it should be followed by a detailed analysis of the identified routes to ensure compliance with the required qualities and where necessary, a recommendation of the infrastructural improvements to achieve these (e.g. provision of cycle lanes, improved crossings at intersections, etc).

Traditional methods of cycle route planning, defined here as those which do not apply SMCA, are incapable of adequately dealing with the conflicting objectives of various stakeholders and multiple spatial and non-spatial criteria used to measure these. It is for this reason that there is growing research into the use of SMCA both locally and abroad. Locally, a method developed by Beukes et al. (2011a, 2011b) that determines the contextual suitability of various modes of transport over a defined area was first applied at a city-wide level in Cape Town, and thereafter Tshwane, to identify where cycling infrastructure is to be prioritised (Beukes & Vanderschuren, 2012). This method however does not identify physical routes but rather the suitability of existing and future planned routes. Internationally, a similar parallel study to that being presented in this paper, by Terh and Cao (2018), applied SMCA in Singapore to assess the suitability of existing routes and prioritise future routes in much the same way as Beukes et al. (2011a, 2011b), but expanded on this by developing first and last mile routes between rail stations and key facilities. The criteria considered in these studies varied, with the former focusing on contextual suitability, and the latter, while acknowledging the importance of and incorporating some route qualities required by cyclists, focused mainly on proximity to select destinations.

3. THE METHOD

The proposed method applies the principles outlined within the "Cycle Network and Route Planning Guide" (Land Transport Safety Authority, 2004) to evaluate and build a network of cycle routes, using an adapted version the method developed by Keshkamat et al. (2009), who used it to develop route alternatives for the Via Baltica Expressway in Poland. A flowchart of the key steps within the method is shown in Figure 1.

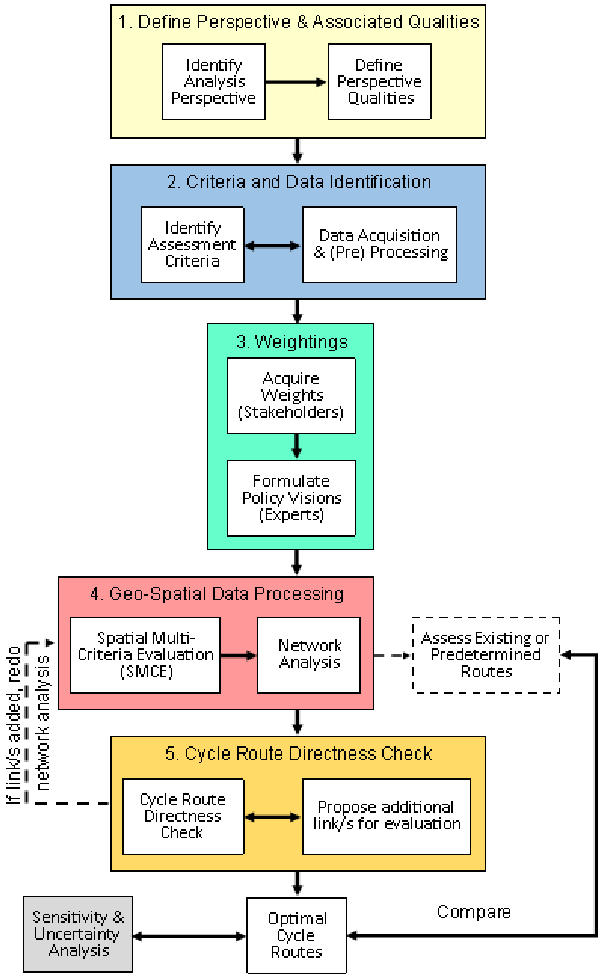

Figure 1: Basic flowchart of proposed method (adapted from Keshkamat et al. (2009))

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, then 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.

A sensitivity analysis of the weights and scores may finally be performed as well. To showcase the method, a case study area was identified to act as a proof of concept.

3.1 Study area

The case study area selected, illustrated in Figure 2, falls within Port Elizabeth, which is situated in the Eastern Cape Province of South Africa.

The circle shown demarcates an area with a radius of approximately 5km. According to the New Zealand Travel Survey for the period 1997/98 (Land Transport Safety Authority, 2004), the South African “Pedestrian and Bicycle Facility Guidelines” (National Department of Transport, 2003), and an analysis of trip length distribution in Dublin, Ireland (Dublin Transport Office, 2006), distances of approximately 5km seem to be the median and up to 10km appear to be reasonable for commuter cycling. It is, however, noted that poorer communities may travel further if required, due to the often captive nature of their trip making. 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.

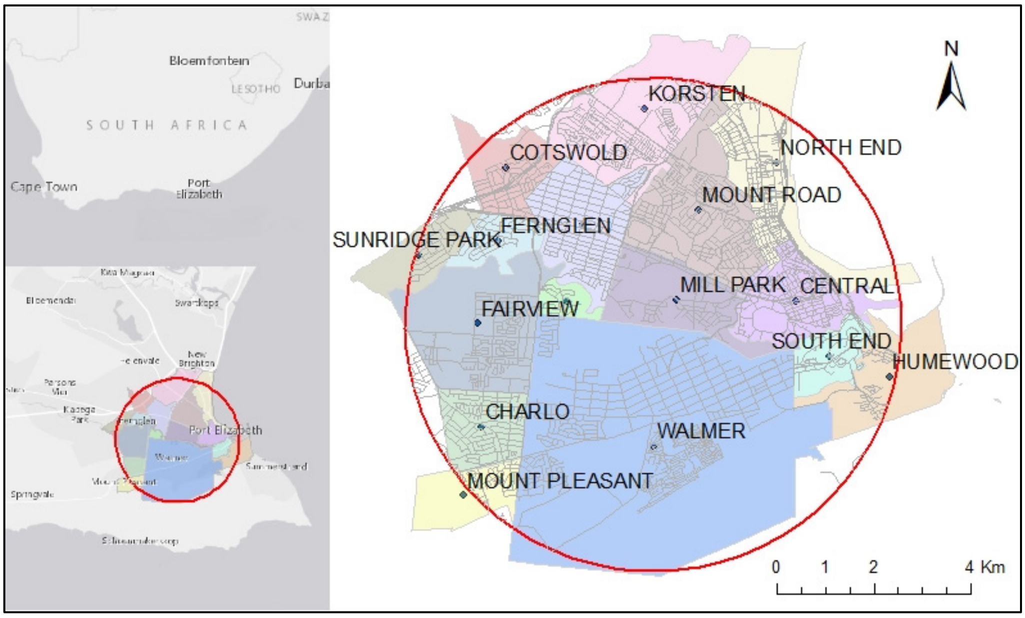

Figure 2: Study area including allotment areas and road network

The site contains a number of wetlands, protected areas, and critical biodiversity areas as illustrated in Figure 3 below, which limit the development of new infrastructure. Wetlands and protected areas are legally protected in South Africa and cannot be developed on, whereas critical biodiversity areas are not and may be developed on if certain requirements are met. This is an important consideration should additional links be required to shorten cycle distances.

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 as shown in Figure 4 below. 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 the analysis, the valley which runs through the centre of the study area across which there are limited crossing opportunities, the escarpment towards the Indian Ocean to the north, and hilly areas to the south all exceed gradients of 5%.

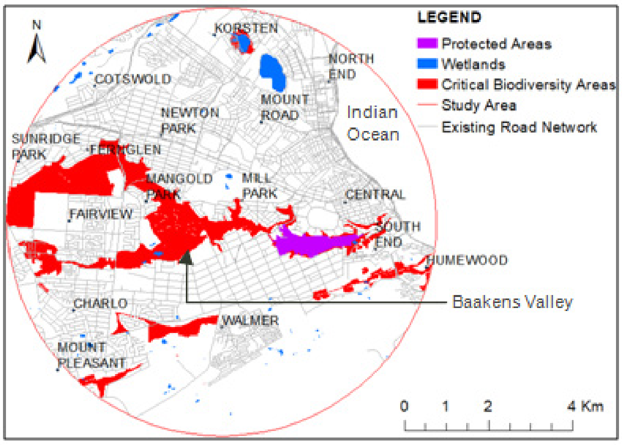

Figure 3: Ecology considered

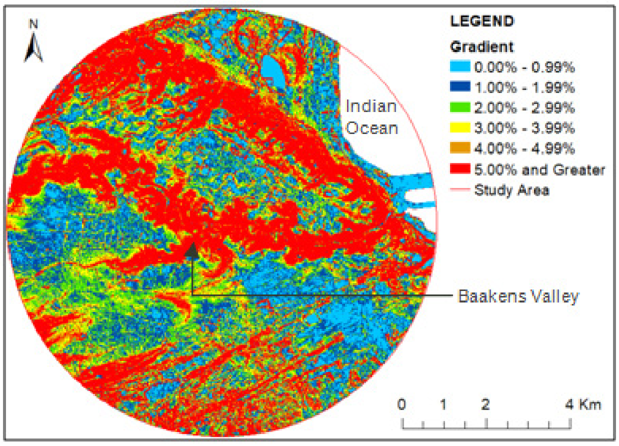

Figure 4: Site topography

3.2 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 facility, 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 in Figure 2.

3.3 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 for example those of technical experts, environmentalists and institutional bodies (e.g. local government). Irrespective of this, if cycling is to be promoted and adopted as a viable alternative means of transport, it is the user's perspective which should be prioritised.

The case study adopts the perspective of commuter cycling (i.e. utility network). General route qualities for this trip type include: (1) safety: intersection types that minimise conflict with traffic and facilities which give them their own space; (2) security: good lighting for evening trips; (3) directness: shortest possible routes to minimise travel time; (4) coherence: continuous routes and networks linking as many destinations as possible; and (5) comfort: gentle gradients and minimal intersections. The study 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.

Of the cycle route qualities discussed in Section 2, 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.

3.4 Step 2: Criteria and data identification

Each route quality defined in Step 1 can be represented by one or more criterion and each criterion is represented spatially by a map. Raster maps are used, as weighted scores according to the criteria can be applied to the pixels forming the maps, which is further discussed in the following steps. 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.

In the SMCA process discussed in Section 3.6.1, 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. Poor performance of a factor can be compensated by good performance of another factor, the combination of which affect the overall performance in the cumulative suitability map. 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 1 below.

Table 1: 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 (Road network)	Spatial cost. The higher the order of the road, the greater the volume of vehicles, number of large trucks, and speeds.
		Intersection Density (Road network)	Spatial cost. The greater the intersection density, the greater the number of potential crossings and points of conflict.
		Street Lighting (Road network)	Spatial benefit. The higher the order of the road, the better the street lighting (assumed correlation for case study).
		Urban Development (Urban cadastral)	Spatial benefit. The presence of development means potentially greater visibility of cyclists.
	Comfort	Gradient (Grid survey)	Spatial cost. Steeper gradients are less appealing to commuter cyclists.
		Intersection Density (Road network)	Spatial cost. The greater the intersection density, the more stopping and starting is required.
	Attractiveness	Critical Biodiversity Areas (As labelled above)	Spatial benefit. Route attractiveness increased by passing close by areas of natural beauty.
		Recreational Areas (NMBM land usage)	Spatial benefit. Route attractiveness increased by passing close by areas of natural beauty.
Environmental	Environmental Conservation	Critical Biodiversity Areas (As labelled above)	Spatial constraint. Future development may occur but it is not recommended.
		Protected Areas (As labelled above)	Spatial constraint. No future development can occur.
		Wetlands (As labelled above)	Spatial constraint. No future development can occur.

The dataset used per criterion is shown in brackets beneath the criterion name. As can be seen, 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.

Proximity to key destinations such as large employers, educational institutions, community amenities, and public transport stations, for example, can be included as criteria for evaluation in the selection of routes. This was excluded from the case study given that an equal latent demand was assumed between the suburbs in the study area as discussed in Section 3.2. The parallel study by Terh and Cao (2018), however, does apply such criteria in their model.

3.5 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.

In the weight assignment process, there is a distinction between the weighting of criteria and qualities. Prior to weighting, the relative importance of criteria and qualities needs to be determined by the various stakeholders, via a ranking process. This can be achieved, for example, using a questionnaire(s) or establishing an elected stakeholder task team to rank the criteria and qualities using one of many accepted methods, including a Likert-type scale or the pairwise comparison method. Thereafter weighting is done using the software discussed in Section 3.6.1, using one of three standard approaches available, namely: direct method (manually assigned weights), pairwise comparison, or rank ordering (using either the expected value method or rank sum method). The sum of the individual weightings of the criteria and qualities must equal 1 (or 100%).

To assist with the ranking of the cycle route qualities, it is proposed that a hierarchy of qualities key to cycling and based on Maslow's hierarchy of needs is used as a point of departure, following van Hagen (2015), who did this for public transport in the Netherlands. Figure 5 below provides an adapted illustration of this hierarchy. By substituting the public transport qualities with cycle route qualities, one is able to create a similar pyramid as illustrated in Figure 6 below.

The hierarchy or ranking of qualities in Figure 6 is better suited to commuter trips, which is the focus of the case study. As noted in Section 3.3, 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.

For the case study in question, as stakeholder engagement was excluded, arbitrary weightings were applied to the criteria and qualities. Pairwise and direct method weightings were applied to the criteria beneath each quality. The weighting of qualities for the commuter cyclist perspective was done using the direct method, in line with the relative importance shown in Figure 6. The weightings applied can be seen preceding each criterion and quality in Figure 7. It is worth highlighting that the environmental criteria do not have weightings, as these are all constraints and therefore always represent a zero (0) value.

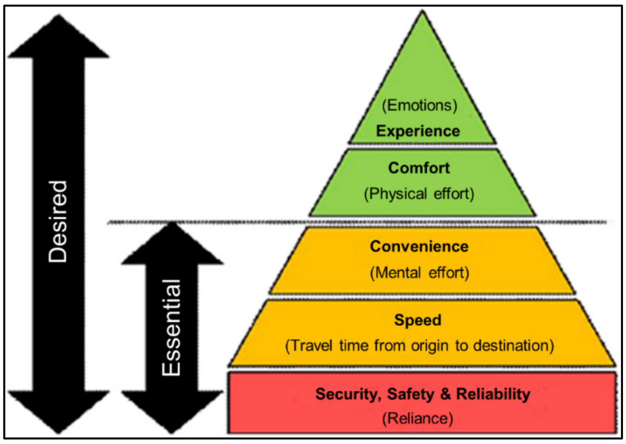

Figure 5: Hierarchy of PT qualities (adapted from van Hagen, 2015)

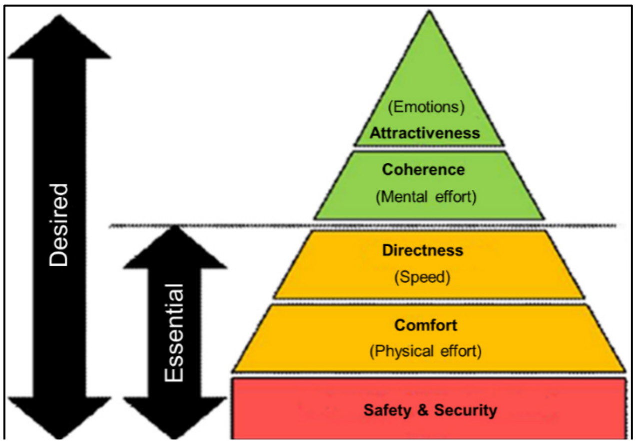

Figure 6: Proposed hierarchy of cycle route qualities

3.6 Step 4: Geo-Spatial Data Processing

3.6.1 Spatial Multi-Criteria Analysis

The SMCA process of the method combines the perspective and associated qualities discussed in Section 3.3, the criteria and geo-spatial datasets from Section 3.4, and the weighting process discussed in Section 3.5.

The software used in this study is ILWIS 3.8.5 (ILWIS, 2015), which is open-source and has a strong SMCA module. To perform the analysis, a criteria tree is 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.

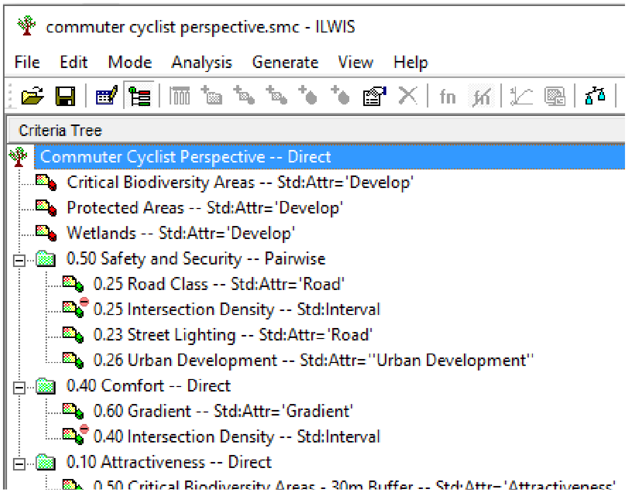

Figure 7: Illustrates the criteria tree developed for the case study

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 7.

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 8. 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. It is worth reiterating at this point that the dark red pixels represent no-go areas (i.e. constraints), which in the case study area are a combination of wetlands, protected areas, and critical biodiversity areas.

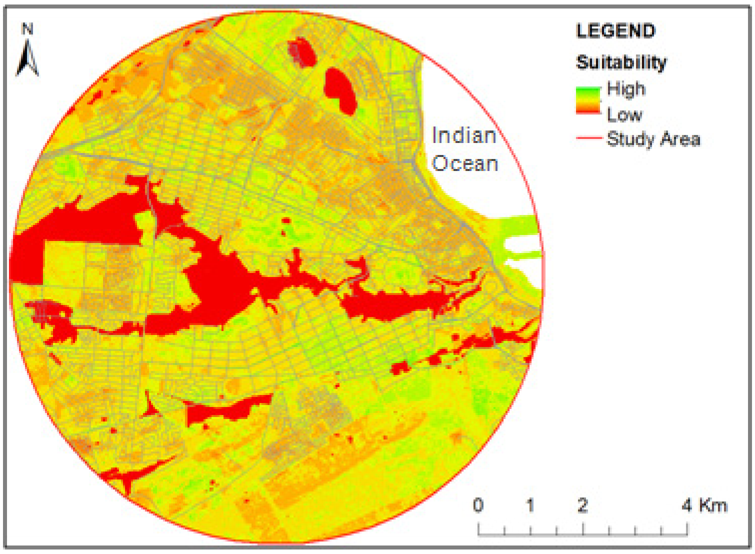

Figure 8: Final suitability map for commuter cyclist perspective

3.6.2 Network Analysis

To develop routes, the raster cell scores from a final suitability map are transferred to a road and/or existing cycle route 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:

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

where l_i is the length of line segment i, v_i is the suitability value of the raster cell beneath segment i, n is the total number of segments in the polyline, and L is the length of the polyline between the 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:

$$\Omega_j = (1 - LWM) \cdot L \tag{2}$$

where Ω_j is the impedance value for polyline j.

The total impedance per route is calculated by summing the individual polyline impedances forming the route using the well-known Dijkstra's algorithm for shortest path analysis in ArcGIS. 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:

$$\Omega_R = \sum_{j=1}^{m} \Omega_j \tag{3}$$

where Ω_R is the total route impedance, and m the total number of polylines forming the optimal route.

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. Figure 9 illustrates the optimal route network generated between all the neighbourhood centroids contained within the study area, as discussed earlier in Section 3.1. It is important to reiterate at this point that as the perspective adopted for the case study was primarily that of a commuter cyclist, the resultant network is better suited to utility cycling.

The total route impedance as per Equation 3 can be used when comparing alternative routings between a common O-D pair. For example, Figure 10 and Figure 11 show the optimal route (developed by the shortest path analysis) and an alternative route between the suburbs of Charlo and Newton Park respectively. The total route length and impedance for the two routes are included in the below figures. It is important to note that although the alternative route is shorter in length, its impedance according to the qualities and weightings considered is greater.

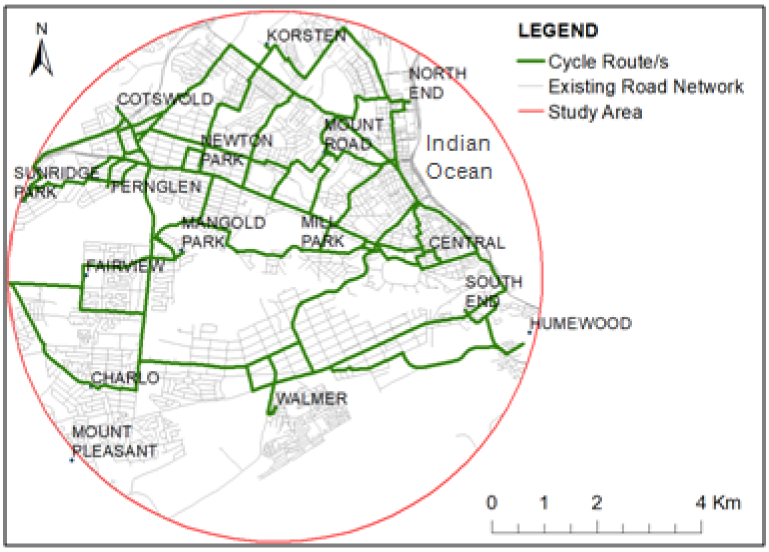

Figure 9: Cycle route network developed using proposed method

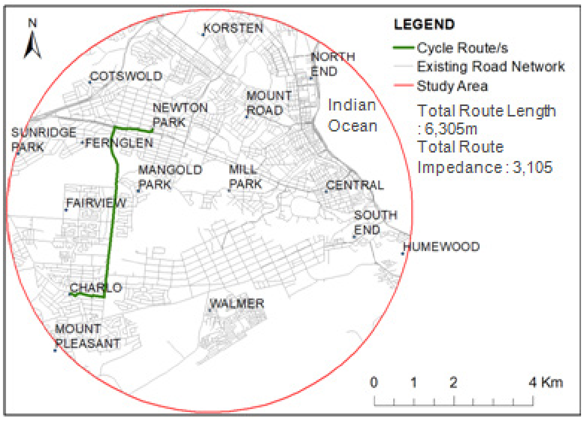

Figure 10: Optimal cycle route between Charlo and Newton Park

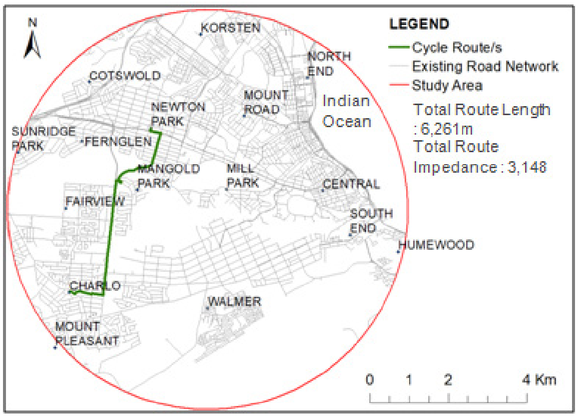

Figure 11: Alternative route between Charlo and Newton Park

3.7 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* is the cycle route directness for route *R*, L_R is the actual route length, and L_s is the Euclidian distance between the beginning and end of route *R*.

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 in excess of 1.6 being considered as indirect. As similar guidelines were not found for CRD in the literature review undertaken, the PRD thresholds have been adopted for CRD until further research has been conducted in this field for cycling. The CRD values calculated at a network level can be found in Table 2.

As with any matrix, the values in Table 2 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.

Table 2: 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

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 12. The effect on routing between select O-D pairs as a result of the additional link can be seen by comparing Figure 12 to Figure 13.

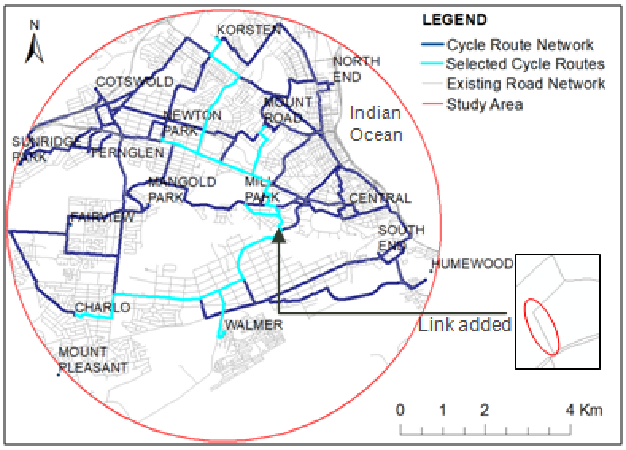

Figure 12: Amended routes between chosen O-D pairs

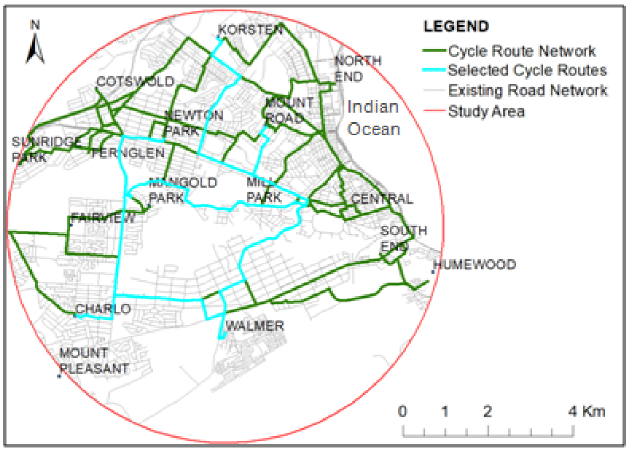

Figure 13: Original routes between chosen O-D pairs

The O-D pairs chosen to illustrate the effect of adding an additional link as well as the original and revised CRD values are summarised in the Table 3 below.

Table 3: Comparison between original and revised CRD values for chosen O-D pairs

O-D Pair	Original CRD	Amended CRD
Walmer – Mount Road	1.56	⬇ 1.47
Walmer – Korsten	1.63	⬇ 1.56
Walmer – Mill Park	2.06	⬇ 1.69
Walmer – Newton Park	1.81	⬇ 1.72
Charlo – Mill Park	1.58	⬆ 1.61

Of the five (5) routes affected, four (4) showed a reduction in the CRD values and one (1) a slight increase. 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 was for the route between Charlo and Mill Park. The reason for this being 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 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.

4. CONCLUSIONS AND RECOMMENDATIONS

The study set out to develop an objective method for the development and evaluation of cycle route networks as its primary aim. The case study undertaken demonstrates that this was achieved as stakeholder engagement is facilitated, it is universal and adaptable and can include a variety of qualities and criteria, it is transparent and back-traceable, and the quantitative scores assigned to routes allow for an objective comparison of alternatives. The intended 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, is easy to understand from a stakeholder perspective when taken through the process. The cost and time to collect geo-spatial data can also be extensive, if not readily available. This can in part be overcome by reprocessing datasets for different criteria as was demonstrated in the case study. However, 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.

In addition to successfully developing routes between defined O-D pairs, the proposed method provides a mechanism to evaluate route alternatives for the perspective under consideration using the impedance score per route, which allows for an objective comparison of routes and is therefore advantageous as it facilitates stakeholder buy-in.

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 authors therefore recommend that there be greater research into the appropriateness of the threshold value between direct and indirect routes for cycling.

Being strategic in nature, the proposed method 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).

The proposed method improves on existing methods as it explicitly considers both the route qualities and length in the development of routes. The route qualities can include requirements from a variety of stakeholders and be weighted in terms of their importance, which are ultimately used to define an impedance per road or path segment. 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.

Lastly, this study adds innovation to the field of SMCA for cycle route planning and prioritisation by: (1) simultaneously solving for a network of routes as opposed to a single route; (2) proposing a relative ranking of route qualities based on Maslow's hierarchy of needs theory and which can be used as a point of departure between stakeholders; (3) suggesting a method of measuring route directness using CRD to identify missing links, and (4) utilising CRD as an additional measure in the prioritisation of cycle facility upgrades.

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