

Configurbanist

Urban Configuration Analysis for Walking and Cycling via Easiest Paths

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In a quest for promoting sustainable modes of mobility, we have revisited how feasible and suitable is it for people to walk or cycle to their destinations in a neighbourhood. We propose a few accessibility measures based on an 'Easiest Path' algorithm that provides also actual temporal distance between locations. This algorithm finds paths that are as short, flat and straightforward as possible. Considering several 'points of interest', the methods can answer such questions as "do I have a 5 minutes 'easy' walking/cycling access to all/any of these points?" or, "which is the preferred point of interest with 'easy' walking cycling access?" We redefine catchment zones using Fuzzy logics and allow for mapping 'closeness' considering preferences such as 'how far' people are willing to go on foot/bike for reaching a particular destination. The accessibility measures are implemented in the toolkit CONFIGURBANIST to provide real-time analysis of urban networks for design and planning.

Keywords: Path Finding, Walking and Cycling, Fuzzy Accessibility, Real Time Network Analysis, Computational Design

INTRODUCTION

Promoting walking and cycling is on the agenda of many cities for developing sustainable urban mobility plans, this is in a way a paradigm shift towards active modes of transportation, which are regarded more healthy and sustainable, namely walking and cycling (Banister, 2008). Increasing the modal share of walking and cycling has been recommended in European Transport top priorities as reflected in EC transport white papers (European Commission, 2001,

2007a, 2007b, 2011a, 2011b). However, policies should be supported by comprehensive knowledge on walking and cycling accessibility; because mobility behaviour in general, and walking and cycling in particular are heavily shaped and influenced by the 'configuration' of built environments, i.e. the geometry and topology of environment. There is a large body of evidence from planning and spatial analysis research on how built environment configuration influences choices of people for walking and cycling

and mobility in general. To have named a few, we refer the reader to research papers such as: (Hillier, B., Penn, A., Hanson, J., Grajewski, T. and Xu, J., 1993), (Hillier, B., & Ida, S., 2007), (Penn, A., Hillier, B., Banister, D. and Xu, J., 1998), and (Banister, 2005).

Apart from evidences in policy and spatial analysis research, common sense also tells us that making choices such as 'to walk/cycle or not to walk/cycle' [e.g. to an everyday destination] has a lot to do with the shape of the city environment. In particular, when making of such choices we think of factors such as how easy it is to get from an origin to a destination in terms of the physical effort and complexity of way finding. Therefore, in planning for walking and cycling [i.e. aimed at increasing the modal share of walking and cycling], we need to be able to measure such difficulties or in other words, the suitability of walking and cycling as modes of transportation as well as accessibility of amenities for pedestrians and cyclists. Specifically, we need to have through knowledge as to how walking/cycling is feasible and favourable at neighbourhood level.

Considering design and planning cases in which it is necessary to weigh options/scenarios for increasing accessibility of pedestrians and cyclists, we propose that we need 'physically sound' knowledge of walking/cycling mobility and accessibility in an applicable form for design and planning practice. We set a goal for ourselves to develop accessibility indicators, which are understandable both for planning/design professionals and citizens.

OBJECTIVE & RESEARCH QUESTION

The main objective of the research behind the development of CONFIGURBANIST is aimed at developing a comprehensive methodology for urban network analysis taking into account the cognitive and physical aspects of walking and cycling in relation to spatial configuration in its geometric and topologic entirety. We try to answer a number of questions related to urban design and planning:

- How suitable is a certain location as to its walking cycling accessibility to a number of amenities and important locations?
- How can we plan a cycling network knowing how people would find the new cycling network favourable?

We do not intend to automate the process of urban planning or design for we find such a goal too simplistic to be of any use; instead, we want to provide the means to assess the effects of different scenarios. It turns out it is not very easy to answer the above questions in a comprehensive manner.

RELATED RESEARCH

Spatial network of cities is mostly comprised of streets and some public open spaces. Topological structure of the spatial network can be generally modelled as either adjacency relations among junctions represented by point features (0D) or streets represented by line features (1D); these two categories can represent links between junctions or streets respectively. We refer to these categories of spatial network representations as Junction-to-Junction and Street-to-Street graphs. The first category is as old as Graph Theory itself and is most common in transport modelling (Dios Ortuzar, J., & Willumsen, L. G. 2011), for it is convenient to measure metric distance on such models. This type of representation is also used in a number of spatial analysis models, namely Place Syntax (Ståhle A., Marcus, L. and Karlström, A., 2008), Urban Network Analysis (Sevtsuk, 2010), and Multiple Centrality Assessment (Porta S, Crucitti P, and Latora V, 2006a). For taking into account the cognitive impedance of going from one street to another, the Street-to-Street adjacency models are more appropriate as they allow for attributing cognitive costs to links between streets. The most famous of this category of models is Space Syntax initiated by (Hillier, B., Hanson, J., 1984) and alternatives such as Named Streets (Jiang, B., & Claramunt C. 2004), Intersection Continuity Negotiation (Porta, S., Crucitti P., & Latora V., 2006b), Angular Analysis (Turner, 2007). Integrating physical

and cognitive impedance in path finding has been researched before as reflected in (Hillier, B., & Ida, S. 2007), Place Syntax (ibid) and Multi-Modal Urban Network (Gil 2014). We have built upon the work of Turner (ibid.) and the Simplest Path of (Duckham, M., and Kulik, L. 2003) and developed an Easiest Path algorithm for finding the paths that are 'as flat, short, and straightforward as possible'. The optimal paths found by our algorithm allow for defining actual travel time or temporal distance and give rise to a number of accessibility measures. What is particularly new in our approach is way we model and aggregate costs, ensuring different costs are physically commensurate. Besides, taking account of topography in the same framework makes it distinctive from similar approaches. Therefore, we can re-define distances as 'actual' temporal distances experienced through easiest paths. Using these temporal distances, we provide a novel framework for accessibility measurements based on Fuzzy Sets theory (Zadeh, 1965).

BASIC DEFINITIONS

When dealing with geometric problems we refer to {Points & Lines [or Polylines]}, in dealing with topologic entities, we refer to {Vertices & Edges}, and in Graph Theoretical context, we refer to {Nodes & Links}. By topological representation, we mean a data model in which small geometric errors such as 'streets not exactly meeting in a junction' do not perturb the graph model deduced. Topological intersections between features of different dimensions (e.g. point to line) are referred to as incidence and those between features of same dimension are referred to as adjacency. A graph Γ (Gamma) is an ordered pair $\Gamma=(N,L)$ composed of a set of nodes N and a set of links L , which can be directed or undirected representatives of adjacencies or incidences. For cognitive cost of travelling, we attribute a Fuzzy (Zadeh, 1965) impedance value showing the angular 'change' of direction to links between streets and for physical cost of travelling we attribute 'the time it takes to walk or cycle a path' given its steepness and length to the

links between streets.

METHODOLOGY

In this section, we 'give a brief overview of the underlying structure of methods implemented in the CON-FIGURBANIST toolkit. Urban design and planning are ever more becoming about intervention instead of creating something from scratch. For this reason, it is of outmost importance to be able to measure the effect of a change in a situation. Such changes are usually simulated in settings usually referred to as "what-if scenarios". An integral part of measuring the effect of design/planning scenarios is analysing built environment and measuring its performance. Suppose we want to measure the quality of a neighbourhood in terms of how good is access of people on foot/bike to a number of destination that are important on a daily basis. In this case, we have to be able to answer questions such as below:

- How favourable is walking or cycling access to an important location for residences in a neighbourhood?
- How good is the access of a location to all/any of important destinations? In other words, how feasible or practical is it for people to travel to their daily destinations by walking or cycling?

Before answering the above questions, we should have answered a more fundamental question that is "what is the easiest way to get from an origin to a destination?" This is firstly to understand how people could travel 'spatially' by walking and cycling. Besides, 'actual distance' or 'experienced distance' is the (spatial or temporal) length of a geodesic (an optimal path). Geodesics are longer than straight lines in urban environments and therefore the notion of distance should be re-defined based on geodesics. There are the two approaches for studying the relation of walking and cycling mobility to the structure of built environment through geodesics, namely, Transportation Planning and Spatial Analysis. Each of these two groups of models have their strengths

but they do not model the entirety of path finding for walking and cycling in that they either disregard the cognitive aspects such as ease of navigation (typical in transportation models) or the physical aspect such as distance and steepness of routes (typical in spatial analysis models). We provide an alternative method of combining physical and cognitive impedance into path finding problem in a 'physically sound' way, which directly leads to a consistent definition of 'experienced temporal distance'. Using this method, we define a number of accessibility measures that are directly understandable for urban planners as well as non-professional citizens.

The process put forward by the toolkit proceeds as follows:

1. Construct a topological model (a dual graph) from street centreline network;
2. Search the graph for 'easiest paths' that minimize physical and cognitive travelling effort, both of which measured in terms of time;
3. Compute the 'temporal distance' of locations from each another;
4. Translate these distances into Fuzzy measures of 'closeness'
5. Aggregate distances of locations towards a number of destinations (alias POI)
6. Answer the questions such as "how close is an origin 'to all destinations' or 'to any destination' of interest?"
7. Divide the neighbourhood into zones of preferred access to a number of destinations (e.g. grocery stores)
8. Compute Closeness Centrality and Betweenness Centrality of the locations as probability indicators of presence or passage of pedestrians/cyclists.

Our research has phenomenological roots but practically proceeds by means of Graph Theory, Fuzzy Logics and Linear Algebra. The first and in a way most challenging step in this direction is to get from a geometric set of lines into a 'connected' graph representation in a systematic manner.

Urban Street Network

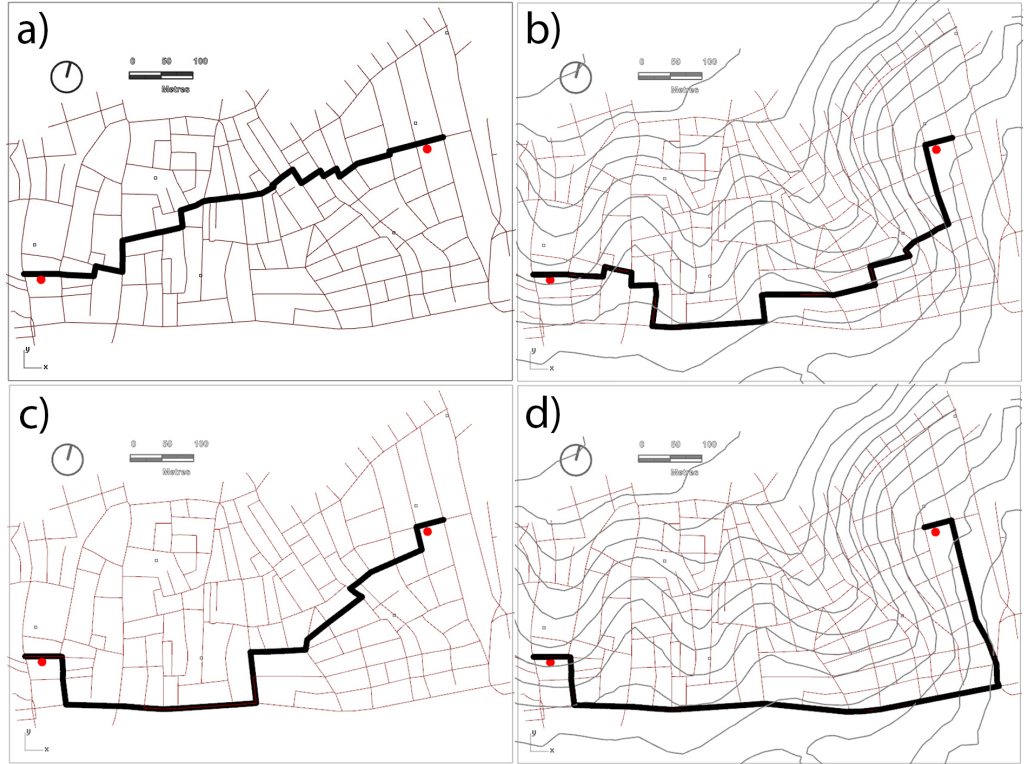
Constructing a street network that is topologically clean and valid is not trivial dealing with real datasets such as OpenStreetMap [7]. In fact, the subject of constructing topological data models of networks is rigorously studied specially for automating such procedures, e.g. see the methods for constructing network topological models for traffic simulations as in (Nielsen, OA, Israelsen, T & Nielsen, ER, 1997). In our work, we have used virtual disks to establish topological adjacency between points and incidence between points and lines. We have adjusted the precision of the road centrelines (polylines) and their vertices through a process of topological voxelization (Laine, 2013), removed pseudo nodes (nodes that do not indicate a street junction); split the street polylines at junctions; and inserted nodes at junctions. By removing duplicate points, we form a list of vertices and by finding incident lines to these vertices; we form a list of topological edges between these vertices. The lines are drawn in both directions to allow for construction of a Point-to-Point directed network. The edges of this network become the nodes of the Line-to-Line graph representation that we use for finding Easiest Paths.

Easiest Path: Optimal Paths minimizing the total costs of traversal

The technical details of this algorithm will be published in a forthcoming paper. Here we give an overview of the models and methods underlying our Easiest Path algorithm (see exemplary outputs in Figure 1). The first step in computing an Easiest Path is construction of a Street-to-Street adjacency graph, whose nodes are directed streets. From each directed edge of a street to another one, there is physical impedance for travelling due to the length of the path and its steepness. The steepness of a path affects the speed of walking or cycling at a normal level of power generation for an average human. Therefore, the slope eventually affects the speed, which based on the length of the path is translated into cost of traveling in terms of time. Note that this cost will

Figure 1

a) Shortest Path without considering the terrain and difficulty of navigation on an example network from "Tarlabasi", Istanbul, data set provided by Ahu Sokmenoglu; b) Easiest Path geodesic found considering the terrain and tau=0 for angular confusion (thereby no cognitive impedance; c) Easiest Path geodesic computed not considering the terrain and tau=15 seconds; d) Easiest Path geodesic computed considering the terrain and tau=15 seconds



be dependent on mode of transportation, i.e. walking or cycling. The other impedance (alias cost) is associated with difficulty of navigation due to demanded change of direction in traversing a street to another. We compute the angle between the direct continuation of a street and the next street and derive a Fuzzy measure of angular impedance that is dimensionless and ranges between 0 and 1, corresponding to no angular change to a full U turn (i.e. 180 degrees of change in movement direction). This is regarded as cognitive impedance of traversing a street to another that is eventually translated into [wasted] time for navigation because of potential confusion in way finding. We do this translation using a parameter dubbed τ (tau), which accounts for

the maximum time that a pedestrian/cyclists would waste at a junction being confusing as to which direction is correct as the next step. The assumption validated by previous research is that people (especially tourists and new comers) tend to follow 'their nose' (Dalton, 2003), meaning people prefer simple paths when it comes to navigation. The overall cost of travelling from i 'th street to j 'th street is then formulated as follow:

$$\zeta_{i \rightarrow j} = Z(\delta, \alpha) + \tau \sin^2\left(\frac{\theta}{2}\right), \delta = \frac{l_i + l_j}{2} \quad (1)$$

$$Z^w(\delta, \alpha) = \frac{\delta}{V_{i,j}^w} = \frac{3.6\delta}{6e^{-3.5|\tan(\alpha_k) + 0.05|}} \quad (2)$$

$$Z^c(\delta, \alpha) = \frac{\delta}{V_{i,j}^c} = \frac{\delta(mg\sin(\alpha_k) + F_f)}{P} \quad (3)$$

Where $\zeta_{(i,j)}$ is the cost of going i^{th} street to j^{th} street and Z denotes physical impedance and is a function of δ (link length) and α is the slope of the link and θ is the planar angle between i^{th} and j^{th} street. The term multiplied by τ represents the cognitive impedance caused by θ and τ represents the amount of confusion attributed to maximum angular change of direction equal to 180 degrees, which can be calibrated later by empirical research. The typical walking speeds are based on the function defined by Tobler (Tobler, 1993) and cycling speed calculation is based on the work of (Allain, 2013). Walking speed and cycling speed when traversing i^{th} street to j^{th} street are denoted as $V_{(i,j)}^w$ and $V_{(i,j)}^c$ respectively. Mass of an average human and their bike is assumed 85 Kg and a nominal friction force of 25 N have been assumed. It is notable that these formulas can be adjusted to represent motor assisted bikes.

Temporal Distance: how long does it take to go from O to D through easiest path possible?

As all costs of travelling are consistently measured in terms of time (minutes), the length of each geodesic (Easiest Path) will be the temporal distance as potentially experienced by a pedestrian or cyclists. Note that we have different cost functions for walking and cycling according to the physics of these modes of mobility, which naturally correspond, to smaller temporal distances for cycling. This all may sound very straightforward now; and this has been the intention indeed. However, this is a remarkable result as there is no other framework consistently measuring actual temporal distance in one to one correspon-

dence with such geodesics. Following our experiential direction in research, we go further in modelling distance as experienced regarding the verbal notion of closeness.

The Fuzzy Concept of Closeness or the Possibility of a Discrete Choice

It is rather obvious that walking or cycling for more than an hour or so is not practical for most people, especially if it is to be a part of their daily routine. This suggests that closeness can be modelled in correspondence with a maximum distance as a threshold above which a person would not be willing to go on foot or bike to a destination. We can measure the practicality of walking and cycling as a function of walking or cycling temporal distance, given a threshold that shows 'how far' (denoted as F) a person is/might be potentially willing to go on foot/bike. Fuzzy variables can range in between 0 and 1 therefore we need a function that can map distance values ranging from 0 to $+\infty$ to values between 0 and 1. Inspired by Logit models in discrete choice models of transportation forecasting models, we choose a Logistic Function as below, which represents the degree to which a statement such as 'destination D whose distance to origin O is x is close by' is regarded as true. Another way of interpreting this measure would be as utility or suitability of walking or cycling as a mode of transportation given a temporal travel distance (see Equation 4 and its plot in Figure 2).



Figure 2
Fuzzy model of closeness given a 'how far' parameter equal to 5 minutes.

Figure 3

a) Fuzzy closeness for cycling from the origin marked (as blue dot) considering the terrain, $\tau=30$ seconds. The sharper the colour the closer the destination; b) proximity to all, supposing people would go as far as 15 minutes on foot to all destination and exceptionally 30 minutes to destination 1



$$C(x) = \frac{1}{1 + e^{\left(x - \frac{F}{2}\right)}} \quad (4)$$

In this equation, $C(x)$ denotes closeness of a destination at a distance x ; and λ represents a coefficient whose role is to ensure the decline of the closeness value when distance x approaches F . Note that the alternative crisp logic representation would be that all destinations farther than F would have been regarded as far and those closer than F would have been regarded as close. Thus, the advantage of this Fuzzy representation should be apparent.

Accessibility Indicators: Fuzzy Logics used to Aggregate Closeness Measures

Here we give two fuzzy definitions of closeness that plainly model feasibility of accessing destinations of interest given the time people are prepared to spend walking or cycling towards them. Suppose for example, there are four grocery stores in a neighbourhood, but some of them are more favourable so people are willing to go somewhat farther on foot/bike to get to them. Such preferences can be modelled simply by attributing a number to each point of interest (POI) saying how far one would be willing to go on foot or bike to get there (see Figure 3 and Figure 4).

Proximity (closeness to all POI)

The 'Proximity to All' (Proximity in short) tells how close a location to all destinations of interest is. It thus tells whether all interesting locations (attractions) are accessible given abovementioned willingness (how far) parameters. Note that if this measure is computed for all possible destinations as potential destinations, it will generate a local closeness centrality measure comparable with local integration in Space Syntax. A number of advantages compared to 'local integration' can be listed as follows: that our measure of local closeness centrality can work for any number of desired destinations; and that its meaning is physically tangible, i.e. does not require pages of explanation; and that it can be interpreted as temporal accessibility as experienced. It simply tells to what extent it would be true to consider all locations (or some locations) as close to an origin, given the maximum distance above which a destination is considered far away.

Vicinity (closeness to any POI)

The 'Vicinity of Any' (Vicinity in short) tells how close a location to any destination of interest is. It thus tells whether any of interesting locations (attractions) is accessible given abovementioned willingness (how far) parameters. This measure is interesting as it can reveal the polycentric nature of a neighbourhood

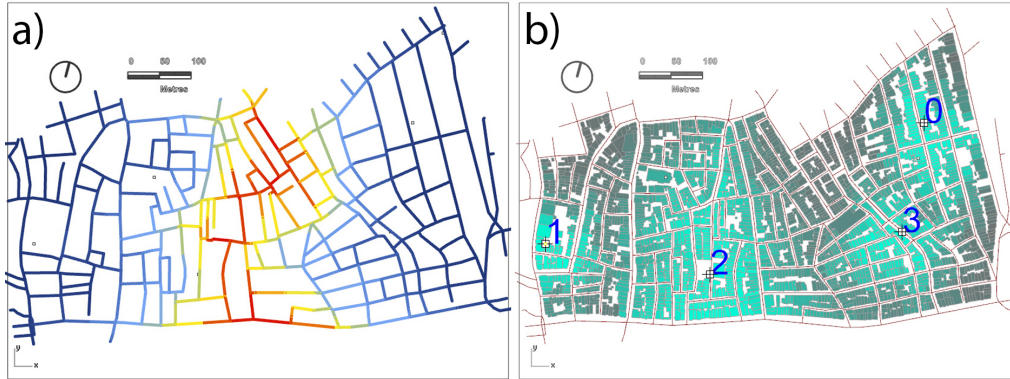


Figure 4
 a) shows proximity to all possible destinations, that is a measure comparable with local integration in space syntax, the colours are chosen to be relative in this case for aesthetic reasons; b) shows vicinity of any POI, when the mode of transport is walking and people are prepared to go as far as 5 minute walking for each point but for attraction number 2 they are prepared to go as far as 10 minutes walking.

given a number of comparably interesting attraction places. More simply, a very straightforward application of this measure is to see whether for instance each location has a reasonable access to a grocery store by walking or cycling. This is important because then such daily routine trips can be made without using personal cars.

Catchment Areas: to all POI or to any POI, using crisp logics

If a simple yes or no answer to questions such as the following are needed then the catchment measure (to all/to any) can be used.

- Are all interesting destinations accessible within 5 minutes walking from here?
- Is any of interesting destinations accessible within 5 minutes walking from here?

Note that the catchment measure proposed here is different from conventional alternatives in that it is polycentric; can be computed to all or any of POI; and that it is based on preferred 'how far' parameters. The catchment measures are computed by treating the fuzzy closeness measures as crisp closeness measures (see Figure 5).

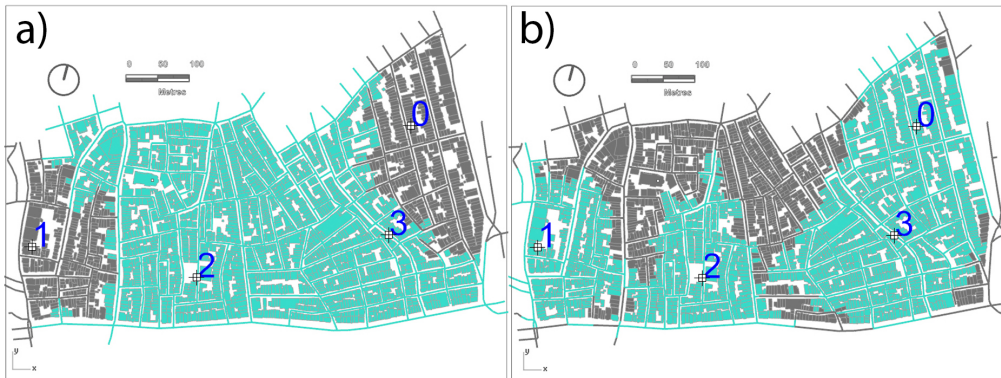
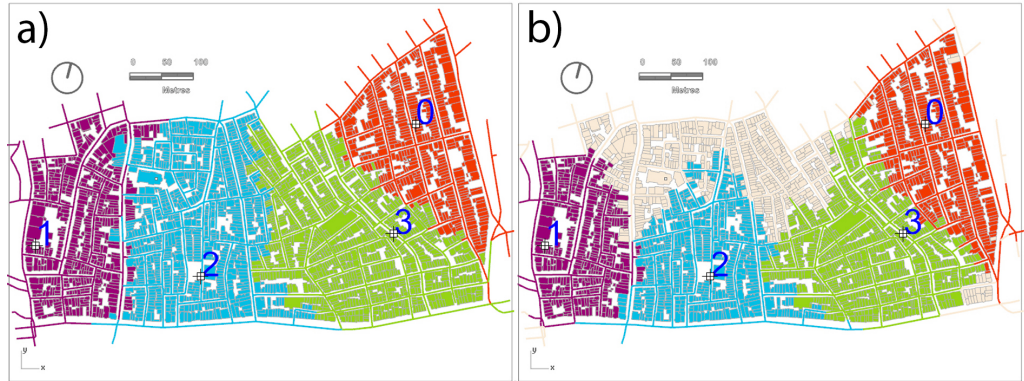


Figure 5
 a) shows proximity catchment (to all POI), walking, considering the terrain and $\tau=15$; b) shows vicinity catchment of POI (access to any POI), walking, considering the terrain when $\tau=15$

Figure 6

a) shows Inclusive Zoning, walking, all acceptable ranges set to 5 minutes. Note that as mentioned above, the inclusive version of zoning determines which POI would be preferred regardless of the fact that it is accessible or not. b) shows Exclusive Zoning for POI, given 'far' as 5 minutes when cycling: Note that this is the same as vicinity catchment analysis with the extra information that we know exactly which POI is preferred where. Note that the pale pink colour shows inaccessible areas.



Zoning for Preferred Access: using generalized Voronoi Diagrams and Alpha-Shapes

Looking at the catchment analysis results, we asked ourselves whether it is possible to tell to which POI each location has preferred access. To answer this question we modelled generalized alpha shapes and Voronoi diagrams (Edelsbrunner, H., & Harer, J., 2008) to divide the network space to areas of preferred POI. This is closely related to vicinity and vicinity catchment (to any). It adds a new dimension to the analysis by specifying how the POI serve/take shares of a neighbourhood considering walking/cycling access. We provide two forms of this measure that we call inclusive and exclusive zoning. The former gives an

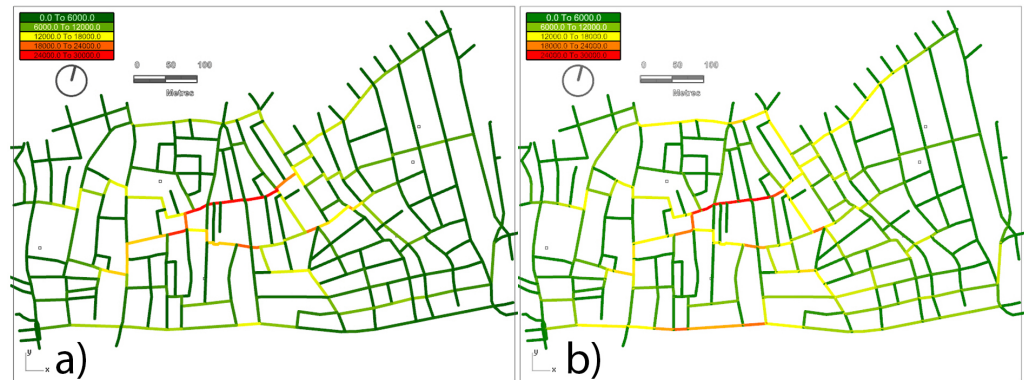
answer regardless for 'which POI is preferred' regardless of whether it is accessible within the acceptable range of distance or not; whereas the latter excludes locations that are by no means accessible (considering the acceptable ranges of distance as specified by user, see Figure 6).

Betweenness Centrality [Revisited]

Using the Easiest Path algorithm and its specific input graph, we can compute a number of centrality measures. These measures are used in network analysis to rank network nodes as to their relative importance. In this case, the nodes are streets in our graph and the links are the junctions between them. Between-

Figure 7

a) walking betweenness centrality without the effect of the terrain and angular impedance; b) walking betweenness centrality considering the terrain.



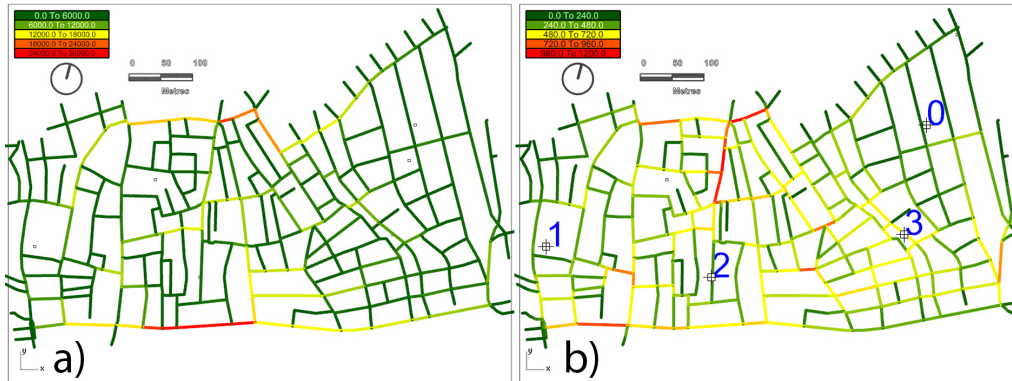


Figure 8
 a) walking betweenness centrality considering the terrain and angular impedance, with $\tau=15$. Note that the southern street is now highlighted as a more important street compared to previous situation.
 b) local betweenness centrality considering the terrain and angular impedances and disregarding destinations farther than 5 minutes

ness centrality literally shows how often a street happens to be on an Easiest Path between an origin and a destination. It is notable that we have revisited the concept of local choice (betweenness in Space Syntax jargon) and made it possible to compute betweenness for a temporal range of distance. We can also compute 'local betweenness' to find out which streets are most likely to be traversed in trips shorter than 5 minutes. As it is the case with any kind of betweenness centrality measure, they essentially look at purposeful trips between origins and destinations but not wandering and lingering. See Figures 7 and 8 for exemplary results.

IMPLEMENTATION OF THE TOOLKIT CONFIGURBANIST

The methods introduced in this paper have been implemented in C# and VB.NET; and then compiled as a DLL and a plugin for Grasshopper(C), a parametric modelling environment for Rhino3D®. The current DLL uses MathNet numerics [5] library for computational Linear Algebra methods operations. The first version of this toolkit was released in 2012. The links for download, Q&A forum page and main page containing more information and notifications on latest developments are provided as QR codes.

DISCUSSION

We provide an algorithm for finding Easiest Paths, in fact easiest possible paths: paths that are as short, flat and straightforward as possible. We do so without comparing apples and oranges, i.e. the physical dimension of all variables included are addressed properly by computing travel costs in terms of time. The distance computed from these paths can be regarded as actual or experienced temporal distance, i.e. the approximate time that would take someone to actually walk or cycle a path, considering both physical and cognitive difficulties along the path in question. We have provided a consistent framework for measuring walking and cycling accessibility in terms of temporal distance to all, any or some points of interests. We can claim that our fuzzy closeness nearly represent human perception of distance -while being mathematically and physically correct- in that they model nearness in terms of temporal distance given easy access to locations. They simply reveal what they say, take for instance the examples investigating whether residences have a reasonable 10 minutes walking or cycling distance to any grocery store; or whether they have walking or cycling access to a grocery store, a train station and a school; and if so, how good is their access? These are the types of questions the tools reliably answer taking into account the physical and cognitive realities of

walking and cycling. In addition, we have reformulated closeness centrality (comparable to 'local integration' in Space Syntax) and betweenness centrality. One limitation to the application of methods, especially in analysing walking mobility is the fact that walking in reality is not bound to street network and can actually take place on grasslands, open squares and alike. This is to say a more comprehensive approach in spatial network representation would be needed to address this issue properly. As mentioned before, preparation of a valid connected graph out of a bunch of street centrelines can be a difficult challenge, especially if the street centrelines are from OpenStreetMap. We have to do some adjustments to our methods to detect the problems in the network and prompt the user to act accordingly. As is the case in most spatial analysis researches, we can only analyse what is meaningfully representable on a map. That is to say, we do not deal with such things as beauty or safety of a route, for we have no rigorous way of measuring them. Therefore, the methods provided can be deemed as describing the potentiality of movement but not its actuality. Centrality measures will be interesting when deemed as probability estimates of some kind of activities. However interesting that prospect might seem, further data intensive research would be required to validate such capabilities. The algorithms are presently only implemented for a parametric CAD environment but we plan to provide them as an add-on for QGIS and they can also be used in routing applications as well as business intelligence applications or wherever knowledge of walking or cycling accessibility can be of value.

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