Development and Application of Circuitscape Based Metrics for Urban Ecological Permeability Assessment

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Abstract: Permeability and connectivity of urban neighbourhoods are related to the spatial configuration of built-up structures and the open space between. Airflow and habitat connectedness are both examples of flows that might depend on these characteristics. Appropriate indicators describing urban neighbourhoods in these concerns are helpful in urban ecological assessment. This paper describes how Circuitscape open source tools for analysing landscape connectivity can be used to develop metrics that indicate permeability and connectivity in an urban environment. It discusses the results when used in urban design.

Keywords: Urban permeability, Circuitscape approach, Geodesign

1 Introduction

Urban Permeability

We know that physical structures and patterns of buildings have an important influence on processes which significantly influence ecological functioning, environmental quality and outdoor comfort in urban areas. Permeability of urban structures is a key metric when describing urban morphology (e. g. ADOLPHE 2001, ALBERTI 2008, BIRAGHI 2019) and when trying to ecologically and environmentally assess urban neighbourhoods. Permeability and connectivity play a fundamental role when considering the urban fabric as a system of patterns and flows in general. However, two very important key effects of permeability of urban structures on ecological and environmental conditions (in the following denoted as urban ecological permeability) can be indicated: airflow and bio-connectivity.

Airflow addresses the dependency of ventilation on patterns of buildings, vegetation, and land cover types in general. When considering the importance of airflow, we have to point out that dilution of pollutants as well as cooling effects depend on the permeability of neighbourhoods. So, air quality and thermal comfort related ecosystem services are addressed by permeability.

Bio-connectivity is a big issue in open landscapes as well as in the field of urban planning, mainly considered in terms of fragmentation and barrier effects on a regional scale. Here the dependency of gene flow, areal shift, dispersal, minimum survivable population size and accessibility of habitat on patch connectedness and matrix permeability in Patch-Matrix systems are the discussed topics. On the local scale, in the densely built up urban core, constructed and managed green infrastructures, which form a well-connected and permeable

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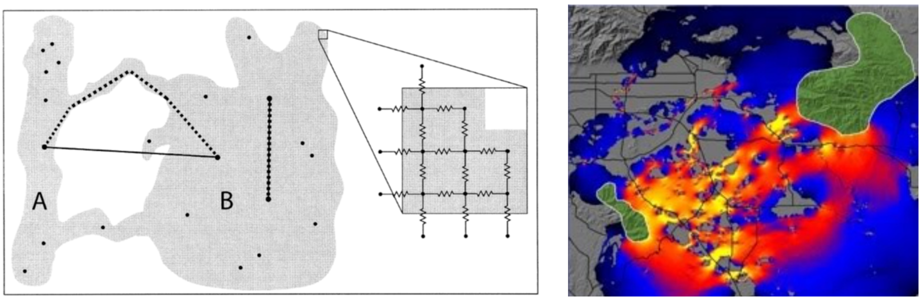
migration network, can help to maintain urban biodiversity and contribute to a lot of cultural urban ecosystem services.

Building density or distance related metrics are often used as a first guess indicator for permeability and connectivity (e. g. Rugosity suggested by ADOLPHE 2001 or Tortuoisity or Constrictivity suggested by BIRAGHI 2019). Such indicators often do not respect configuration of structures and thus do not explicitly consider the ease of movement as a basic target of any permeability indicator.

What is Circuitscape?

"Circuitscape" is both a model approach and a model application software to identify landscape connectivity and permeability in respect to gene flow and based on the "Isolation by resistance" concept published by Brian MCRAE (2006)[1]. The concept assumes a source and a target region and calculates resistance for the space continuum between the source and the target (discretized and represented by grid cells respectively by a corresponding lattice of connected nodes; Figure 1). Then resistance is interpreted as it is handled in electric circuit theory and is a property assigned to each node. The clue is that if we assume this analogue, Kirchhoff's Law[2] applied to the landscape lattice leads to the characterisation of the conductance and the current at each node (grid cell). MARROTTE et al. (2017) discuss similarities and differences of the approach compared to Least-Cost-Path analysis.



(a) (b)

Fig. 1: (a) Components of spatial concept of "Circuitscape" are individuals living in suitable habitat (grey), movement between A and B, and discretization of movement space by an electric circuit network for which resistance distance is calculated. (b) Example of a result (current strength map) (MCRAE 2006, https://circuitscape.org/).

Apart from gene flow, Circuitscape is used in many areas, ranging from animal movement to fire propagation, water movement and disease spread (DICKSON et al. 2019, MCRAE et al. 2016). Over the past ten years, Circuitscape has proven to be the world's most cited software tool for networking landscapes (DICKSON et al. 2019).

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[1] In the following both approach and software are addressed by „Circuitscape"
[2] For a detailed explanation refer to MCRAE (2006) and MCRAE et al. (2008)

Can Cicuitscape Help to Indicate Urban Ecological Permeability?

In the densely built-up urban cores both aspects of ecological permeability, airflow and bio-connectivity, depend on green infrastructures and their spatial arrangement plus the grey and blue infrastructures. All together can be transferred into a resistance grid, which is representing the degree of inhibition of movement. Therefore, the concept of Circuitscape can be applied as it is usually used in open areas if a plausible resistance concept is fixed.

In many cases, urban planning focusses on neighbourhoods, often represented as a spatial unit delineated by roads or other linear elements like rivers or land cover separating borderlines. In a next step, neighbourhoods are then characterized by specific metrics, which indicate demographic, socioeconomic, physical or biophysical characteristics.

This article shows how Circuitscape approach can be applied to urban neighbourhoods, and that it is able to indicate permeability as a precursor of airflow and bio-connectivity favour. We suggest metrics for permeability, which describe the degree of a neighbourhood being permeable. We show that the suggested metrics deliver non-contra-intuitive results and are worth to be tested as universal permeability indicators.

2 Material and Methods

Our application of Circuitscape demonstrates the evaluation of urban neighbourhood units concerning ecological permeability (airflow, bioconnectivity). In a first approach, this is done by a 2D representation of buildings inside the unit. Buildings are assumed impermeable, space around the buildings are assumed open for passage. This simplification is reduced by introducing surface roughness when considering airflow or by identifying obstacles influencing species-specific movement or dispersal. We took data from Open Street Map (OSM), and the method is tested for neighbourhoods representing different building patterns (e. g. single houses, block edge structured, linearly structured).

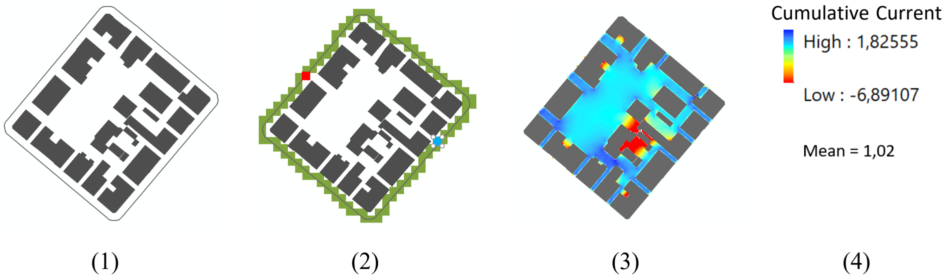
To be able to use Circuitscape in permeability assessment of a neighbourhood two fundamental problems have to be solved. (1) As Least-Cost-Path analysis, Circuitscape requires the specification of a source and a target region. How to do this when there is no logical definition of sources and target areas? (2) Circuitscape visualises spatially explicit consequences of resistance on current. How to aggregate current values of raster cells to get a metric that can be used as an aggregated permeability indicator for the complete neighbourhood?

As an appropriate method the authors suggest to take the neighbourhood delimiting raster-cells (let N_d be the count of delimiting raster-cells) both simultaneously as source raster-cells and as target raster-cells (step 2 in Figure 2). This leads to a cumulative current map (step 3 in Fig. 3) being the result of $(N_d - 1)^2$ pairwise current calculations. The cumulative current map then can be compared to a current map, which is calculated for an undisturbed situation, i. e. for an empty neighbourhood polygon without buildings.

In a final aggregation step for cumulative current values of the raster-cells of a neighbourhood unit an aggregating statistic must be calculated to get a permeability indicator value for the neighbourhood unit. We suggest two metrics:

(1) *Overall Flow Impact (OFI).* This indicator is calculated as the standard deviation of current, and it identifies the overall impact of buildings on current flow when the buildings are introduced to an "empty" and undisturbed neighbourhood.

(2) *Total Obstruction (TO) and Total Obstruction Density (TOD). TO* is calculated by the sum of raster-cell differences in current between "empty" and built up neighbourhood. *TOD* relates *TO* to the area under consideration.



Step 1: Buildings and border of a neighbourhood
Step 2: Raster-cells intersecting borderline are used as source/target
Step 3: Cumulative Current map, which indicates current flow inbetween all pairs of border raster cells
Step 4: Aggregation by statistical key figure as indicator value for the neighbourhood

Fig. 2: Illustration of Circuitscape application on an urban neighbourhood

Two scenarios concerning resistance are considered. (A), there is no difference in between the buildings and resistance is set to 1 for all raster cells. In scenario (B), we illustrate the respond of the suggested metrics to green structures introduced scenario like as an intervention. In this scenario we assign to the raster cells the resistance of trees which is assumed as 100 times the resistance of plain surface. This assumption is made by plausibility considerations oriented to BRAAKER et al. (2017), who worked on hedgehogs, in respect to bio-connectivity, and to roughness length of different surfaces as reported by GRASSI et al. (2012) concerning wind.

The calculations of the indicators assume a voltage of 1 and have been done using Circuitscape extension for ArcGIS (https://circuitscape.org/downloads/) included in an ArcGIS 10.7.1 model builder tool.

3 Results

Figure 3 shows 2 examples of current maps for different types of neighbourhoods, a) a compact bloc structure neighbourhood near the city-center and b) a more scattered single house structure in the periphery. Both examples produce similar maximum and range of current flow. Considering case a) current is intensified at suitable passages whereas in case b) a more homogenous height of flow can be observed. This leads to a lower standard deviation and thus lower *OFI* in case b) compared to a) as an impact of the more compact configuration of buildings. Total obstruction Density *TOD* also shows a lower value in case b). Here and in Figure 5 it can be seen that *OFI* and *TOD* are inversely related to permeability.

a) Bloc structure in central city
OFI = 0,2566
TOD = 1,1541

b) Single house structure in periphery
OFI = 0,0740
TOD = 0,3050

Fig. 3: Suggested metrics for two different settlement structures

Like in gene flow analyses, Circuitscape helps to characterize special locations in a neighbourhood permeability analysis. In both examples of Figure 3 current is at the lowest level (red) if flow in narrow physical niches is considered. At a bottleneck-situation, we can observe an increase of current, and when having excluded grid cells with negative current, which identify non-accessible space, we can define movement area (Figure 4).

A widespread practice to assess permeability is to simply use Building Density (*BD* = area covered by buildings / total area). Figure 5a documents the result of an experiment, which successively adds some buildings and thus monotonously decreases permeability. Metrics

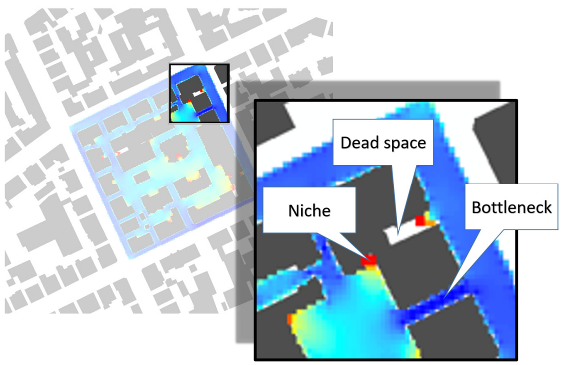


Fig. 4:
Identification of specific locations

OFI and *TOD* respond in an increase accordingly. Figures 5b and 5c show, that the suggested metrics differ in the corresponding comparison example while *BD* is nearly the same. Circuitscape based metrics respect building configuration, reflect consequences of building arrangement concerning permeability und thus closely interfere with the physical design of neighbourhood structure. Considering the same amount of building area in scenarios for a case study area *BD* does not vary, whereas configuration of buildings can be optimized in regards to permeability when controlling *OFI* and *TOD*. So *OFI* and *TOD* can easily be used as control parameters in a Geodesign environment.

Circuitscape applications target to include and to study resistance effects of different landscape structures. In Figure 6 we demonstrate that the suggested permeability metrics respond to resistances assignments e. g. as specified above in chap. 3. The introduction of trees leads to a very evident increase of *OFI* and a moderate increase of *TOD*.

4 Discussion, Conclusion and Outlook

From its theoretical background as well as from its computational implementation the approach presented is appropriate to address urban permeability. OFI and TOD behave monotonous and steady when being calculated under an increase of obstructing structures and thus can be used as indicators for permeability. It is helpful to describe neighbourhoods by the suggested metrics. For instance, results can be used to create an urban permeability choropleth map which can be overlaid e. g. by local wind systems representation or a species habitat map. The advantages of Circuitscape approach can be summarized as follows:

(1) Other approaches (e. g. ADOLPHE 2001, BIRAGHI 2017) to describe urban morphology in terms of permeability suggest, to calculate different mertrics which consider partial aspects. This leads more or less to a permeability profile that is not easy to be included in further analyses or in clear planning considerations.

(2) In the field of bio-connectivity, there is agreement that it depends on the characteristics of the species under consideration whether a Circuitscape or Least Cost Path approach is recommended (MARROTTE & BOWMAN 2017). The subject of Circuitscape application in this paper is the characterization of neighbourhoods. Here Least Cost Path approach doesn’t provide any useful application.

(3) In the field of urban airflow, CFD-models are commonly used. Here as a direct modelling method fluid mechanics is applied on urban morphology. However, input data and computation time are the limiting and often preventing factors when discussing the application of CFD-models even if only used in 2D. Circuitscape approach suggests to use an analogy model which can be successfully run only with an urban surface resistance layer. Our examples show that the main questions in urban planning can be answered by the approach: locations of interest and an overall assessment of obstruction.

(4) It is fruitful to use the proposed method in a Geodesign workflow (e. g. SCHWARZ-V.RAUMER & STOKMAN 2014) if a comprehensive indicator is needed on ecological permeability at a rough level of detail. Here the method provides much more information compared to building density. In particular, it responds to different test configurations of buildings, which have the same density of buildings. From a technical point of view, the method requires less skills, less specialized software and less computation time compared to other solutions.

Future work will compare applicability of the suggested approach with established methods (e. g. ENVI-met). We will calculate a permeability map for the complete metropolitan area of Stuttgart and demonstrate its usability in urban planning and design at landscape scale.

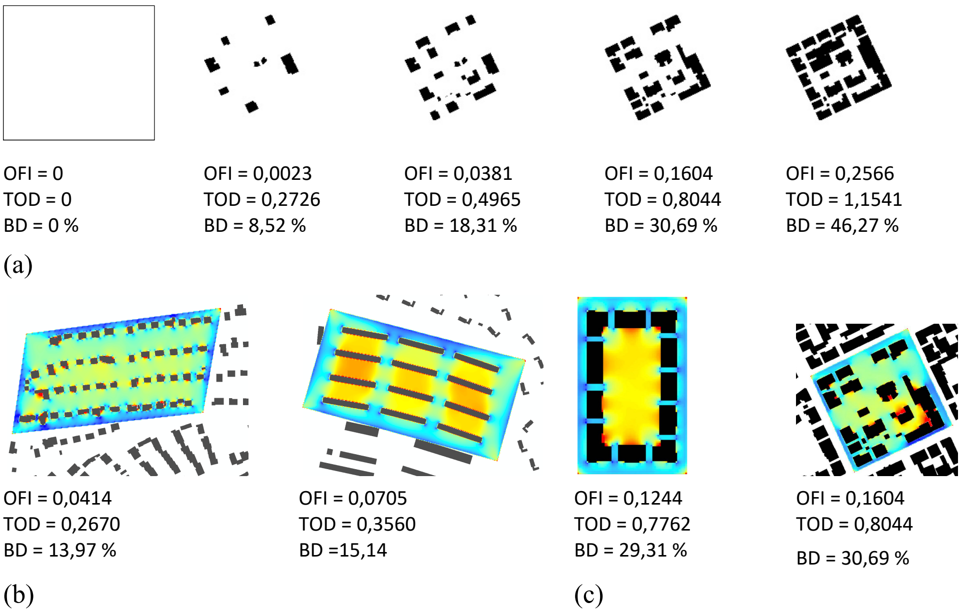


Fig. 5: Comparison of Circuitscape based metrics with building density *BD*

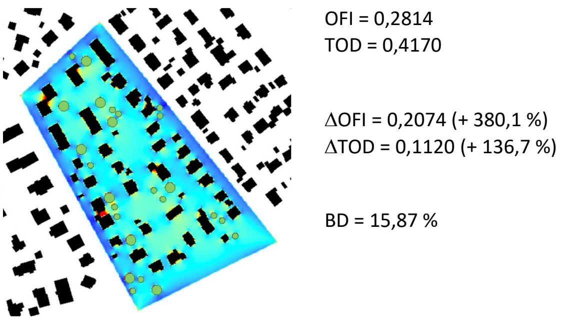


Fig. 6:
Case study area b) from Figure 3 in a scenario which considers tree planting (dark green circles)

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