



Identifying European Sustainable Mega-city Regions with Multi-dimensional Network Percolation

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Abstract

Territorial structure significantly conditions the sustainability of human settlements. Recent forms of urbanization, in particular integrated mega-city regions, may imply different patterns of economic and transportation flows and thus exhibit various performances regarding different indicators of sustainability. This paper proposes to reconstruct endogenous urban regions from the bottom-up using network percolation, in a multi-dimensional way to take into account both urban form (spatial distribution of population) and urban function (properties of transportation networks). Variable parametrizations allows to consider patterns of optimization for two stylized contradictory sustainability indicators (economic performance and greenhouse gases emissions). This suggests a customizable spatial design of policies to develop sustainable territories.

Keywords

Road network; multilayer percolation; mega-city region

I INTRODUCTION

The structure of road networks both translates its past growth dynamics and has a significant impact on the sustainability of territories it irrigates. Diverse methods to characterize the structure of spatial networks, and more particularly road networks, have been developed in that context.

A method to characterize topologies of these spatial networks is network percolation. Such approaches have been applied to the modeling of urban growth ([Makse et al., 1998](#)) and to the analysis of street networks for example to extract endogenous urban regions ([Arcaute et al., 2016](#)) or to characterize the spatial morphology of point patterns [Huynh et al. \(2018\)](#).

Existing heuristics however generally focus on a single morphological dimension of networks, and leave out the functional properties of urban systems (Burger and Meijers, 2012).

This paper addresses such a gap by introducing a multi-dimensional percolation heuristic.

We percolate the population density layer with a network characteristic layer, that we test among number of edges, number of vertices, cyclomatic number and euclidian efficiency, which capture functional properties especially for the two last.

II METHODS

2.1 Multi-dimensional percolation

Given discrete spatial fields, site percolation is operated between two cells given a threshold parameter for each dimension and a distance threshold. This heuristic is similar to multilayer network percolation Boccaletti *et al.* (2014).

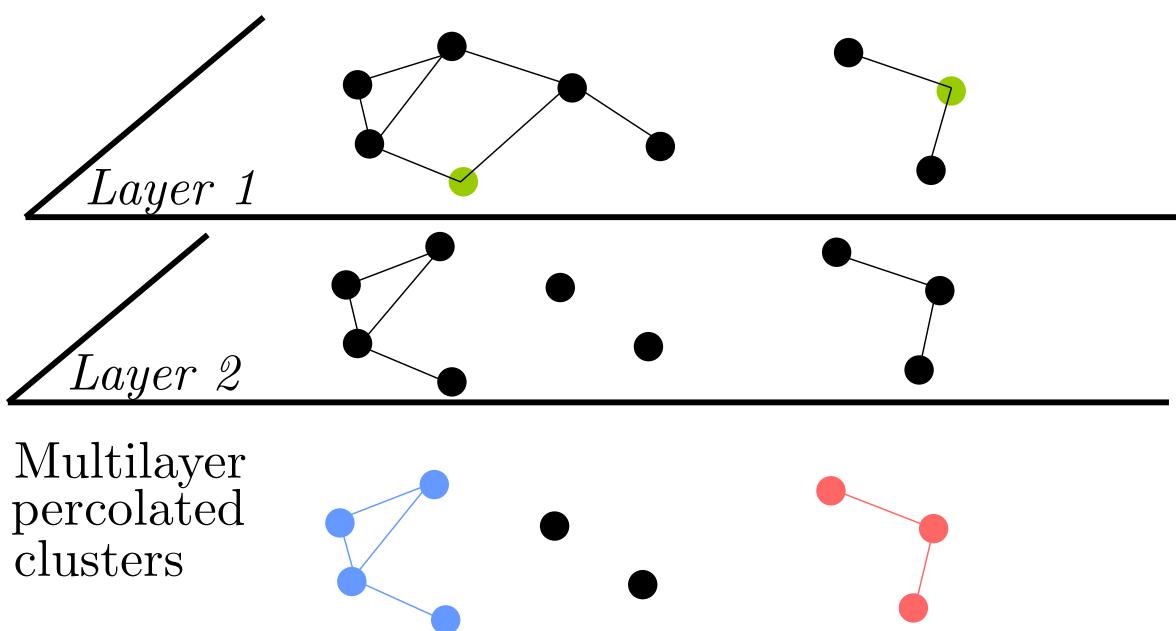


Figure 1: Schematic representation of the multi-dimensional network percolation heuristic.

2.2 Empirical data

We apply the heuristic to urban morphology and road network topology measures in Europe. More precisely, a grid with resolution 50km of population density morphology indicators and road network topology indicators, has been computed on spatial moving windows for all European Union by Raimbault (2018).

2.3 Sustainability indicators

We use this endogenous definition of regional urban systems produced by the percolation algorithm to evaluate their sustainability, in terms of conflicting objectives of economic integration and greenhouse gases emissions. The definition of sustainability, or sustainable development, is by essence multi-dimensional (Viguié and Hallegatte, 2012). Its characterization as quantitative indicators is even more subject to numerous degrees of freedom. We work here with two stylized indicators for two conflicting dimensions, as a proof-of-concept.

The EDGAR database ([Janssens-Maenhout et al., 2017](#)) (version 4.3.2) is used for local estimates of greenhouse gases emissions.

Applying a gravity model to each region, we estimate abstract transportation flows within each and extrapolate emissions by coupling with the Edgar emission database ([Janssens-Maenhout et al., 2017](#)) and economic activities with a scaling law of population. More precisely, greenhouse gases emissions derived from economic and transportation flows are estimated with the following expression

$$\phi_{ij} = \left(\frac{v_i v_j}{(\sum_k v_k)^2} \right)^\gamma \cdot \exp \left(\frac{-d_{ij}}{d_0} \right) \quad (1)$$

where v_k are either effective local GHG emissions or population. Indeed, the economic activity follows relatively well scaling laws of populations [Bettencourt et al. \(2007\)](#), the exponent being dependant on the activity and the definition of areas on which it is estimated ([Cottineau et al., 2017](#)).

The sum of all flows within the geographical span of the cluster (that we approximate as the convex Hull envelope of its points), allows us to approximate the cumulated potential emissions and economic activity.

III RESULTS

3.1 Implementation

In practice, the analysis is implemented using R and the igraph package. The network is constructed by superposing the population density layer with the network layer.

The experience plan is a full grid, for parameters r_0 , θ_P , θ_N and the network variable considered.

We systematically explore the clusters obtained for 4800 parameter configurations.

3.2 Extracting endogenous mega-city regions

Maps reveal that most configurations resemble the actual distribution of European mega-city regions, which are functionally integrated polycentric urban areas ([Hall and Pain, 2006](#)). These are here defined endogenously from the bottom-up.

3.3 Pareto fronts for sustainability

We show therein that different population, network and distance thresholds yield different performances in terms of sustainability, exhibiting a Pareto front. This suggests policies in terms of regional integration to increase the sustainability of mega-city regions.

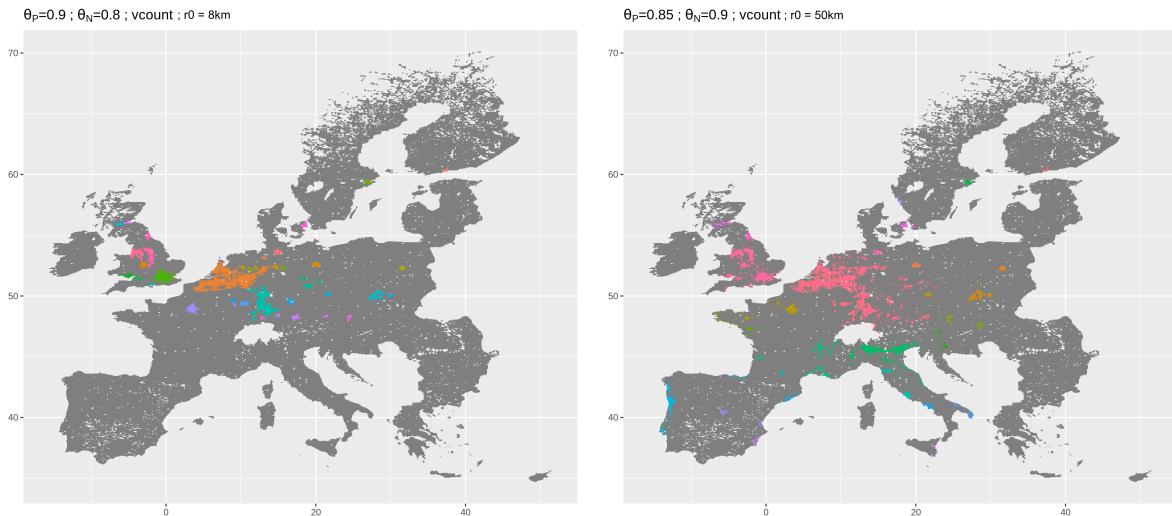


Figure 2: Two examples of obtained clusters for different parameter values.

3.4 Linking urban morphology and sustainability

When considering the aggregated indicators for a parametrization of endogenous city regions, one can relate them to morphological indicators, computed by , that we average on areas. This establishes a link between urban morphology and sustainability. A principal component analysis on considered points yield 96% of variance with two components, and 73% explained by the first component alone. The first component relates to a level of monocentricity ($PC1 = -0.3 \cdot I + 0.54 \cdot \bar{d} + 0.51 \cdot \varepsilon + 0.59 \cdot \alpha$). As shown in Fig. ??, there seems to exist an optimal intermediate level of monocentricity regarding emissions only, except for long-range and low-hierarchy interactions. However, when considering both emissions and economic indicators, urban form then acts as a compromise variable, moving points on Pareto fronts, as shown in Fig. ???. In some case, highly monocentric areas can be a good compromise, whereas the intermediate optimal for emissions may yield highly inefficient areas.

IV DISCUSSION

Further work will consist in the use of calibration heuristics (Reuillon *et al.*, 2013) to find in a more robust way optimal parameter values.

V CONCLUSION

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A APPENDIX 1: SUPPLEMENTARY SENSITIVITY ANALYSES

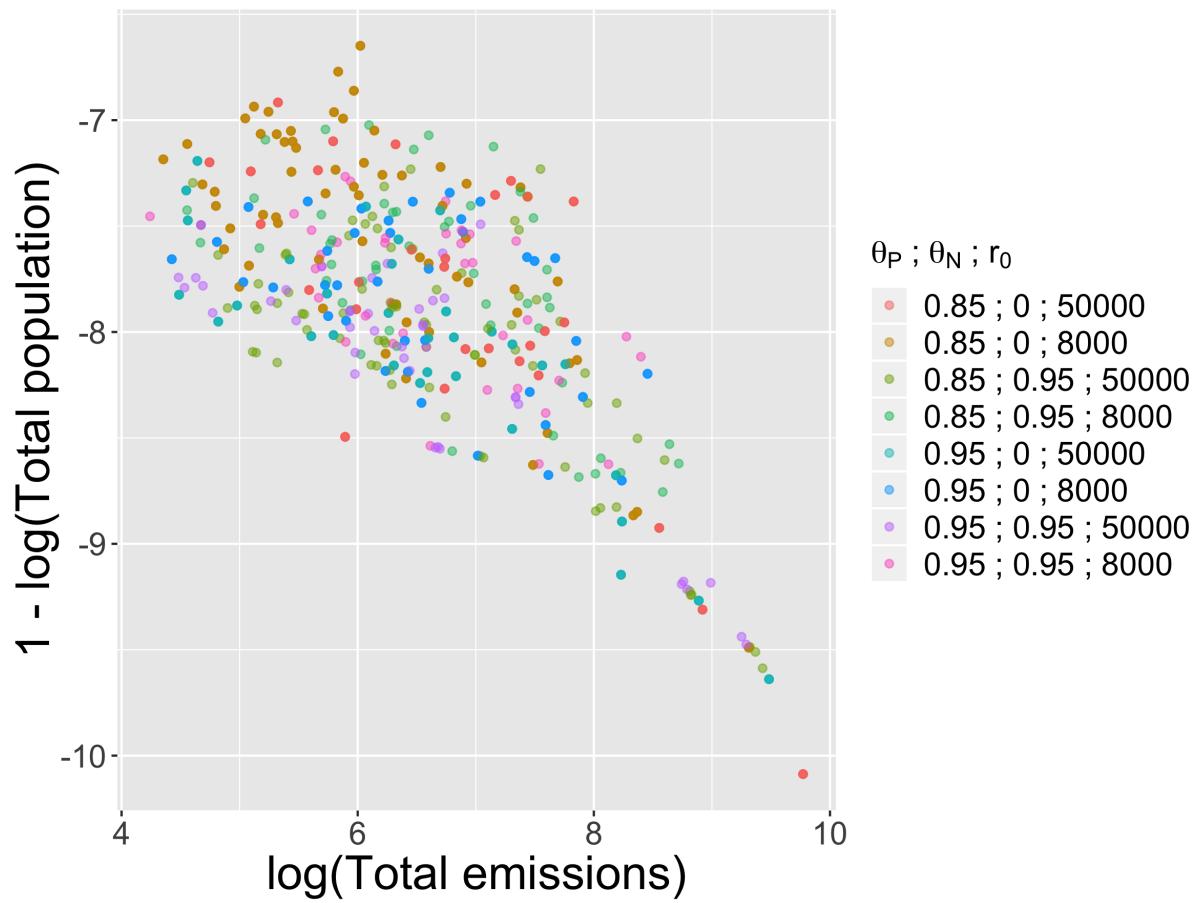


Figure 3: Point clouds of region-level indicators, namely population and emissions, for different parametrizations.

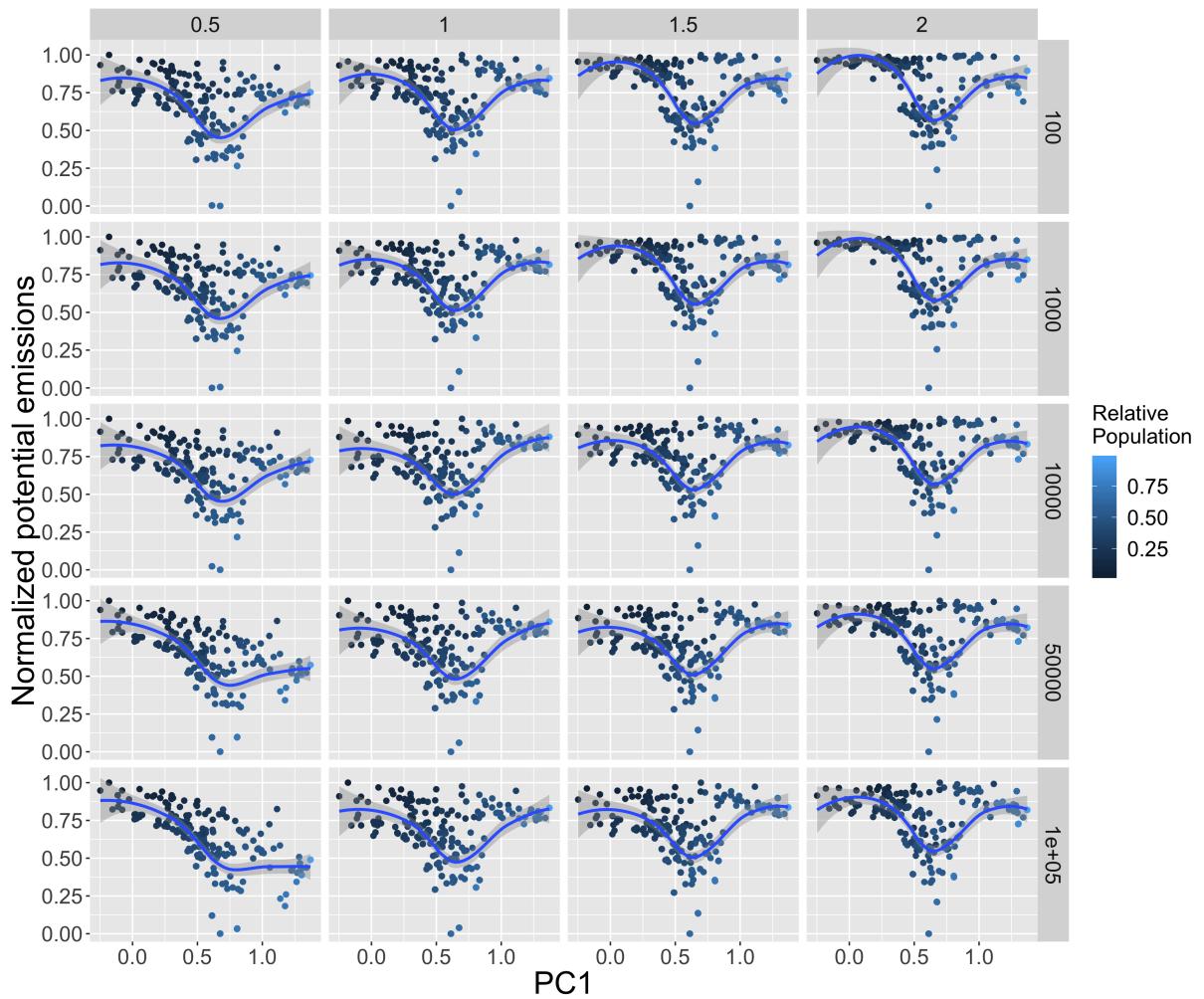


Figure 4: Aggregated values of normalized potential emissions, as a function of the first morphological principal component (PC1), for varying values of parameters d_G and γ_G . As PC1 is mainly linked to monocentricity, there seems to exist an optimal intermediate level of monocentricity for emissions alone.

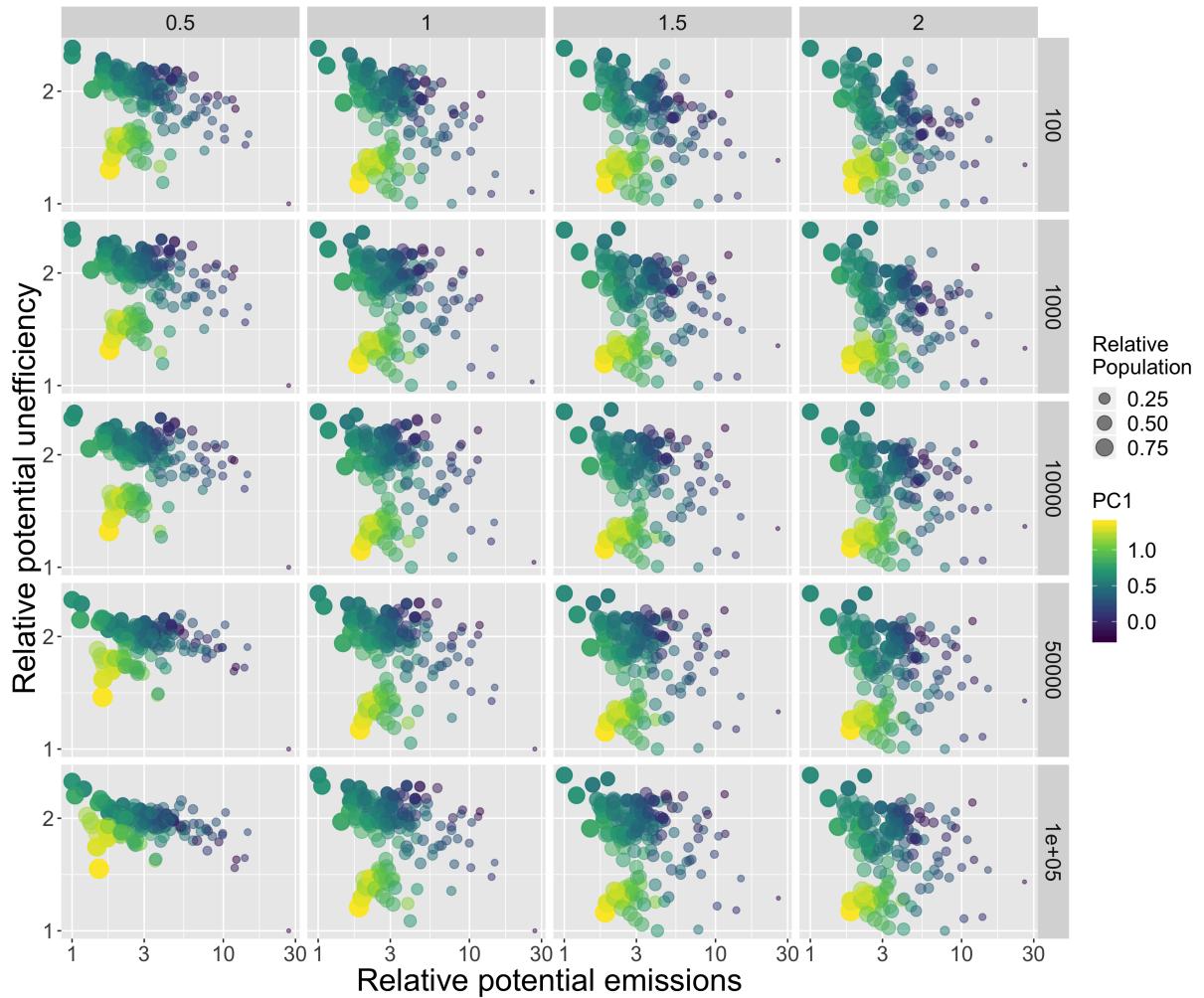


Figure 5: Relative potential emissions against relative potential economic unefficiency (both indicators should be minimized), for varying values of γ_G (columns) and d_G (rows). Color level gives the value of PC1, whereas point size gives the share of total population contained within considered areas.