The AXS Model: an agent-based simulation model for urban flows

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It is well known that movement patterns have an influence in urban form and land use distribution in cities. The paper presents the AXS Model, which generates an aggregated movement pattern from the bottom-up using an agent-based modelling approach. The aim of the AXS Model is to replicate global urban patterns, such as the ones generated by accessibility and centrality measures, from the bottom-up by simulating the movements of individuals in the city. Preliminary results from a pilot study for the Greater London area show similarities between movement patterns and those generated by accessibility and centrality metrics. The next step of this research is to simulate more realistic movement patterns by adding real origin and destination points from land use data and by differentiating the agents into groups with different preferences and behaviours.

Keywords: Agent-Based Models, Urban Flows, Accessibility, Centrality.

1. Introduction

Although ephemeral, flows can have a lasting effect on city organisation, affecting decisions taken by people regarding where to live, set up business and carry out other activities. Thus, flows can be identified as an important factor shaping urban form while being shaped themselves by a series of urban and environmental factors including: land uses, which are the origins and destinations of trips; infrastructure and terrain characteristics, which can make it easier or harder to use different routes; cultural aspects and collective memory, which can make people prefer one route over another and so on.

Urban movements have been extensively studied and modelled. The most traditional way is through Spatial Interaction Modelling, which considers transport costs and level of activities between pairs of locations to calculate the number of trips generated between those locations (Wilson 1971, Chang 2006). More recent studies take advantage of new technologies to simulate and analyse flows in disaggregated scale using agent-based modelling techniques (see a review in Maggi and Vallino 2016).

These movement patterns are related to urban measures such as accessibility and centrality, which have also been related to residential and commercial location as well as urban growth and development patterns in larger scale. This study proposes an agent-based simulation model, entitled AXS, which aims to replicate such global patterns from the bottom-up by simulating the movements of individuals in the city. The technique developed here can be extended to simulate more complex movement patterns by differentiating agents' behaviours and preferences, by generating trips based on real land use distribution in the city, and by including different transport modes. This flexibility constitutes an advantage of the agent-based modelling approach over traditional graph-based accessibility and centrality measures.

2. Model Description

The AXS model generates aggregated flows patterns by accumulating the paths chosen by a set of individual agents when moving through an environment, which is represented in grid space. The model can be run in abstract environments as well as in real cities by importing GIS data for the study area. The model's current inputs are the urbanised area and the road network in vector format, which are then converted to raster format inside the model and the resulting information stored in the grid cells. In the model, moving agents represent flows of people and goods in the city. Each agent is created at a random point of the grid and is assigned a destination cell to move to during the model's execution. Both origin and destination points are located within the urbanised area. Each agent has limited knowledge of the environment, defined by *search-radius* and *angle-of-vision* parameters.

Every model iteration, each agent scans its neighbourhood and selects a subset of cells which are closer to its destination. The subset is defined by the parameters *angle-of-vision* and *search-radius* which, together, define a cone of cells in front of the agent. The agent then analyses the selected cells and chooses one to move to, based on the cell's proximity to the destination and to the road network. Agents are free to move through the whole grid, but they try to minimise the effort of moving by using the road network whenever possible. Finally, the agent moves to the selected cell, and the flow counts of the traversed cells are incremented. Agents who reach their destinations are removed from the simulation and replaced by new agents created at random positions, keeping the number of agents constant during the simulation. This algorithm is illustrated in figure 1, below.

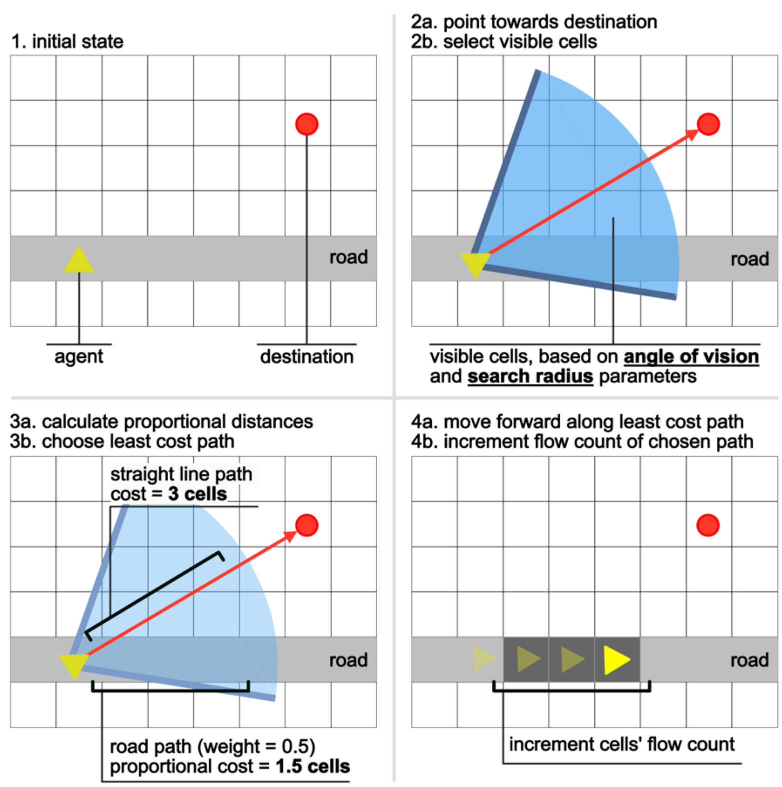

Figure 1 - Agents' walking procedure in the AXS model.

3. Case Study

The model was applied to the Greater London Authority (GLA) area[1]. Only the main road network of the study area was included in the simulation. The information was extracted from OpenStreetMap, from which only the roads tagged as 'motorway', 'primary' and 'trunk' were selected (Figure 2). Using a more detailed representation of the road network would demand a higher grid resolution, which was set at 200m for this simulation (resulting in a grid of 325x275 cells).

Figure 2 - Greater London Authority area and primary road network.

The simulation was run with 100 agents, with the search radius set to 3 cells and angle of vision set to 80º. Figure 3 shows four snapshots of the simulation, where it can be seen that the aggregated flow pattern emerges relatively fast after a few iterations, and consolidates between 100 and 200 iterations (a complete animation of the process can be seen at https://vimeo.com/205420253).

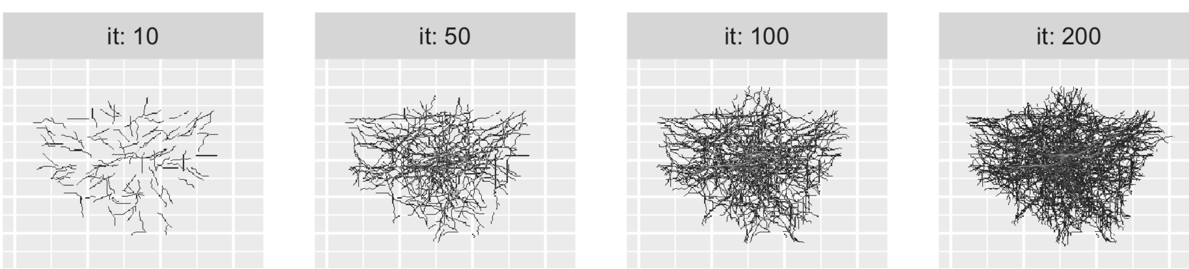

Figure 3 - Aggregated flows in iterations 10, 50, 100 and 200.

The spatial distribution generated by the AXS model was compared to the spatial patterns of accessibility and centrality measures. These measures are calculated for networks of urban streets using graph

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[1] The model's source code, developed in NetLogo, and the R scripts containing the statistical analyses presented in this paper can be found in the GitHub repository https://github.com/mvpsaraiva/axs_london

techniques, from which the global structure of such networks can be analysed. For this study, the street network of the Greater London area was represented following the dual approach (Porta, Crucitti, and Latora 2006), where streets (in the form of axial lines) are represented as nodes and the intersections between them as edges in a graph.

The accessibility measure, in its most essential form, is based on proximity, and can be defined as the property of an element to be closest to all other elements of the network, considering the shortest (or preferred) paths between them (Ingram 1971). Mathematically, the measure is defined as in equation 1:

$$A_s = \sum^{s \neq t \in V} \frac{1}{d_{st}}$$

Equation 1

That can be read as: the accessibility of element *s* equals to the sum of the inverse of the distances between elements *s* and *t* of the network.

The centrality measure used in this study is based on betweenness, and can be defined as the property of an element to be in the shortest path between pairs of other elements of the network (Freeman 1977). Mathematically, the measure is defined in as in the equation:

$$C_v = \sum^{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Equation 2

That can be read as: the centrality of element *v* equals to the sum of the number of shortest paths between elements *s* and *t* where *v* lies on, divided by the number of shortest paths between *s* and *t*.

The results of the accessibility and centrality measures for the Greater London area are shown in Figure 4. Accessibility presents a smoother distribution in the urban fabric, reducing gradually from the city centre towards the periphery. Centrality presents a more concentrated distribution, in comparison with accessibility. A few streets concentrate the higher values of centrality, which decay sharply towards the urban edge.

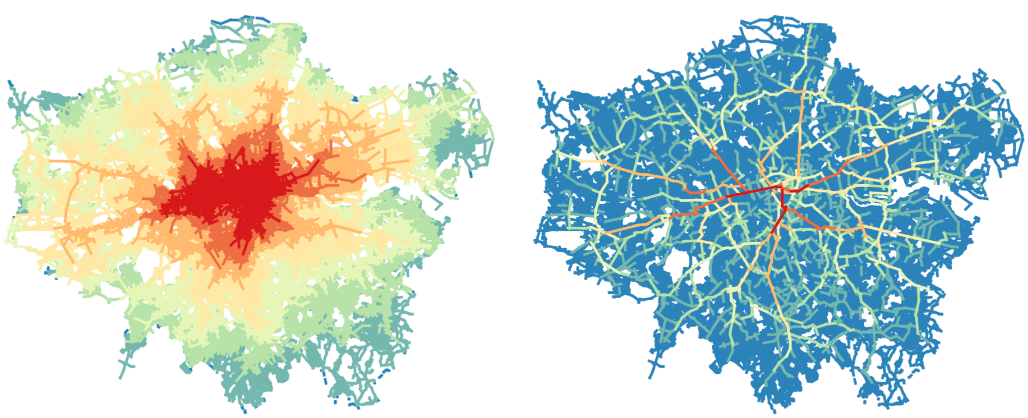

Figure 4 - Accessibility (left) and centrality (right) patterns for Greater London.

The graph-based measures were converted to raster using the process of Kernel Density Estimation, or KDE (Longley et al. 2011). This method calculates the density of features for each observation point using a kernel function and a bandwidth parameter, generating a continuous field. Four values for the bandwidth parameter of the KDE algorithm were used: 250m, 500m, 750m and 1km. The same process was applied to the aggregated flows grid, thus converting movement counts into movement densities, thus considering the neighbourhood effect of urban flows. The results are shown below, in figure 5.

Figure 5 - Flows, accessibility and centrality densities calculated using the KDE method with four bandwidths.

The accessibility and centrality measures in raster format present similar patterns to the original measures in vector environment: accessibility varies smoothly from centre to border, while centrality decreases sharply. The accumulated flows measure presents an intermediate pattern in relation to the later ones. In all measures, the increase in bandwidth results in smoother grids.

The scatterplots (Figure 6) show a stronger positive correlation between the aggregated flows and the accessibility measure. The correlation between the aggregated flows and the centrality measure is also positive, but significantly weaker. Both correlations increase with the bandwidth, indicating that the aggregated flows measure is more capable of identifying urban patterns in larger rather than local scales.

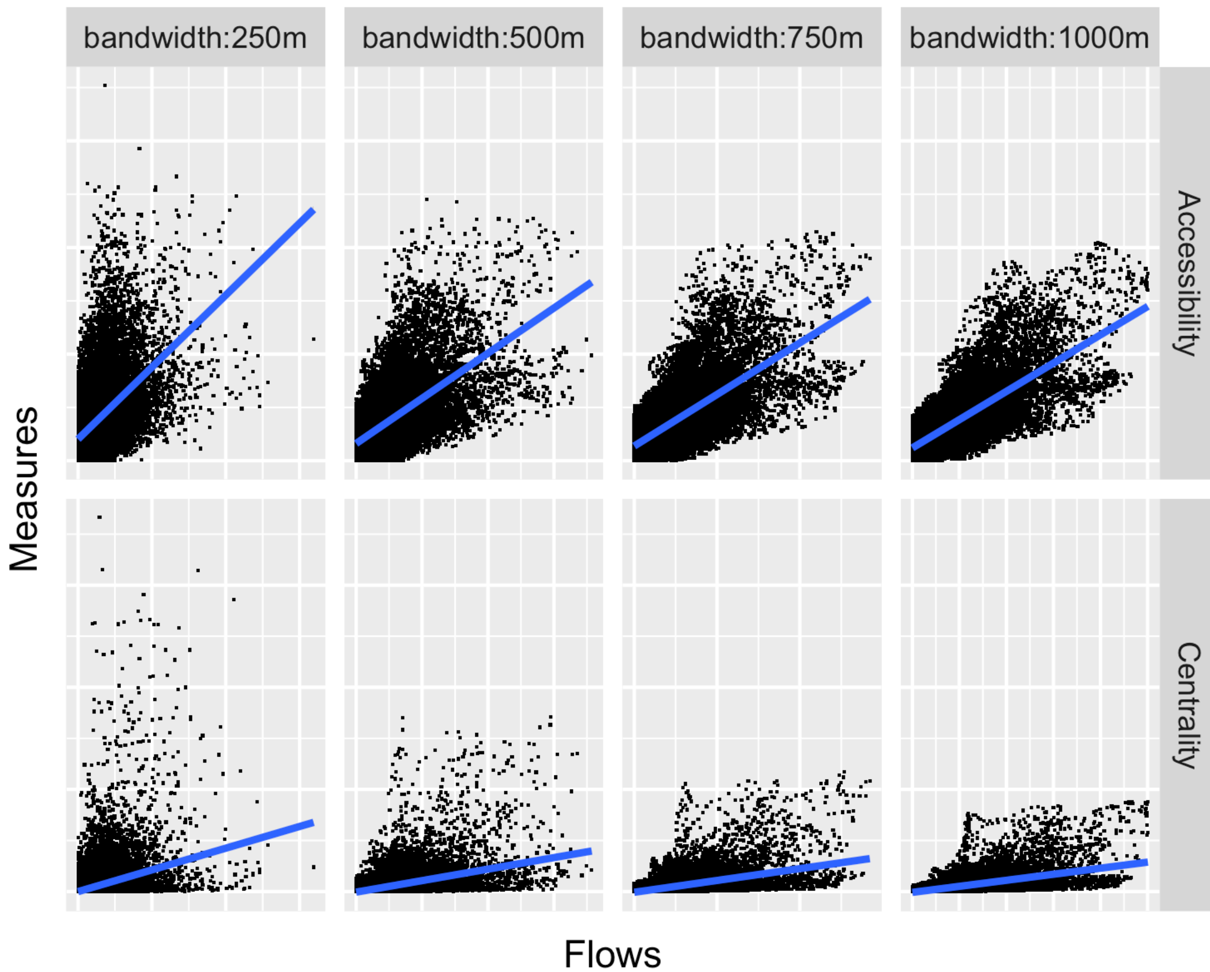

Figure 6 – Scatterplots showing the correlation between aggregated flows and accessibility and centrality grids.

The correlation indices shown below in Table 1 are average (0.52 for accessibility) to low (0.37 for centrality), for the bandwidth of 250m. These values are significant considering the simplicity of the model, both in agent's behaviour and input data, and the small bandwidth of 250m in relation to the size of the work area. The correlation indices increase steadily with the increase in bandwidth, getting to 0.74 for accessibility and 0.59 for centrality when the bandwidth is set to 1km.

Bandwidth	Accessibility	Centrality
250m	0.52	0.37
500m	0.64	0.48
750m	0.70	0.54
1000m	0.74	0.59

Table 1- Correlation coefficients between aggregated flows and accessibility and centrality grids.

4. Conclusions and Further Work

The current version of the AXS model introduces a simplified agent-based simulation of urban flows, based on random trip generation and movement facilitated by, although not restricted to, the road network. Even in this simplified version, the model was able to simulate an aggregated flows pattern which resembles the overall urban structure based only on local agent-environment interactions.

The further improvement of the model presents an opportunity to further investigate urban flow patterns and their relationship to accessibility and centrality in urban systems. A change from grid environment to a road-network environment is planned for the next stage of the research, to add more realism to agents' movements while avoiding the need of data conversion and sampling. More complexity will be added to the trip generation aspect of the model, which may include more realistic origin-destination pairs based on real land use distribution in the city. Finally, more complex behaviour will be added to the agents themselves, as they may belong to different social groups and have different preferences and behaviours, or use different transport modes.

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