Route Choice Through Regions by Pedestrian Agents

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Abstract

Simulation models for pedestrian movement are valuable tools to support decision-making processes in urban design. However, existing models of pedestrian behaviour are built on simplistic assumptions regarding people's representation of the urban space and spatial behaviour. In this work, a route-choice algorithm that takes into account regionalisation processes and the hierarchical organisation of geographical elements is adapted for pedestrian movement and incorporated into an agent-based model. The macro-level patterns emerging from two scenarios, one employing an angular-change minimisation algorithm and the other employing the regional algorithm here proposed, are compared for a case study in London, UK. Our routing algorithm led agents to recur to a higher number of street segments, i.e. routes were more diverse among agents. Though validation has not yet been performed, we deem the patterns resulting from the regional algorithm more plausible.

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1 Introduction

The movement of people in cities, be them cyclists, pedestrians, drivers and transit users, has proved to be one of the most challenging subjects of study in urban dynamics research [21]. Urban travellers interact with the city environment and its manifold phenomena, shaping the city form as well as its economic and cultural structures. As such, gaining insights into people's movement and spatial behaviour may support cities in decision making as concerns transport infrastructure, wayfinding signage design, service allocation and urban configuration redevelopment.

In this context, geosimulation is considered a tool which "enhances our understanding of how cities function and evolve in space-time" [8, p. V]. In particular, Agent-Based Modelling (ABM) allows researchers and experts to understand how individuals' goals and choices mould flows at the macro level [7]. However, the ability of these models to capture such dynamics depends on the theoretical assumptions and design considerations of the modeller

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about how an agent formulates routes across the urban environment [12]. In most of the existing representations, agents' route selection processes are modelled as functions derived from utility theory [1]. Herein, it is assumed that urban travellers make spatial choices and thereby generate routes by assigning costs to different alternatives. A utility measure is pursued and computed by the agent on the basis of time, distance or attractiveness [13, 17].

Simulation models for pedestrian movement in urban contexts are quite sporadic. Even harder is to find exhaustive attempts to implement cognitive representations of space in ABM. A set of works has been inspired by the Space Syntax approach and the idea that the configuration of the street network guides pedestrian movement [9]. Penn and Turner [16], integrating Space Syntax techniques and ABM, enriched agents with information regarding visibility at junctions. Jiang [10] devised an ABM for pedestrian simulation whose main postulate is that the interaction between agents and the street configuration alone may account for the self-organisation of pedestrian patterns. More recently, Omer and Kaplan [15] designed an ABM wherein agents choose destinations on the basis of a land-use attractiveness measure, and employ different kinds of path-selection criteria (Euclidean distance, number of turns and angular change minimisation).

These models mainly make use of street segments properties along the lines of utilitaristic approaches to spatial behaviour and, furthermore, do not contemplate agents endowed with symbolic representations of the urban space. Yet, other geographical elements are known to be important. Kevin Lynch [11] and successive research in cognitive geography widely suggest that individuals' representations of the city are built upon multiple categories of urban elements – nodes, paths, districts, landmarks and edges –, which are significant with respect to spatial behaviour, navigation and human-environment interaction. Moreover, several studies have gathered empirical evidence on the hierarchical organisation of these elements in human knowledge [14, 20], a type of structure which reflects the "degree of recognition and the idiosyncratic relevance of individual objects" [4, p. 257] in the urban environment. These findings may prompt a more realistic and complete representation of individuals' spatial behaviour in simulation models [6, 13].

The aim of this work is to advance an ABM for simulating pedestrian movement which embraces a cognitively-grounded, hierarchical routing framework. We include in the simulation a route-choice model built upon the framework presented in [13], adjusted for pedestrian movement. Therein, the author advances a bounded-decision making approach to route-choice behaviour in light of findings on the hierarchical organisation of spatial knowledge relative to urban elements, and regionalisation processes. In our ABM, we introduce a scenario in which agents are equipped with a simple cognitive, two-level hierarchical representation of the urban space, which comprises a coarse regional division of the city and fine-grained information about main street segments and junctions. Macro-level patterns emerging from the inclusion of such elements in the simulation are compared to the outcomes emerging from a scenario in which agents use a single-level cost-minimisation approach.

2 Methodology

In the ABM for pedestrian movement simulation here introduced, *agents* – representing walkers – complete trips through the *environment* – the street network of the case-study area – between pairs of origins and destinations (OD). Two different scenarios are designed: in the first case, agents use the common single-level utility approach, minimising angular change – *AC scenario* –, in the second, they employ the routing model presented below, here called regional routing algorithm – *RR scenario*.

The model proposed by Manley [13] embodies different planning levels in the route-choice process by representing an initial rough global plan, subsequently refined at higher granularity levels. This framework was designed and validated with taxi driver routing data and it is here adjusted and integrated into an ABM for pedestrian movement.

In summary, at first, nodes are extracted from a multilayer network and ranked by a centrality measure. Afterwards, functional regions are identified from the street network by means of a community detection technique, and finally employed within the route-choice model. Therefore, in the ABM, a spatial hierarchy is built at two levels: nodes are classified by salience and manipulated accordingly for the extraction of OD pairs; concurrently, a containment hierarchy is represented by a two-steps decision process, from the urban- to the street-level, when formulating a route.

Nodes and districts identification

Cognitive salient nodes are anchoring points, easy to remember and associated with the procedural component of the spatial knowledge. Centrality measures have proven to be able to differentiate between primary and secondary nodes [5]. In [6], *betweenness centrality* is employed to extract main nodes from the street network. However, we claim that the transit network should also be taken into account to capture meaningful urban nodes. Considering different urban layers, their interactions and their structure, allows to better understand how places are connected [19]. Therefore, the betweenness centrality of a node is here computed through a multilayer representation of the urban system [3] composed of two layers, the road network and the transit network (see figure 1 a).

Euclidean distance is used to weight links in the two networks as well as transfer edges (i.e. the distance between the street junction and the public transport station).

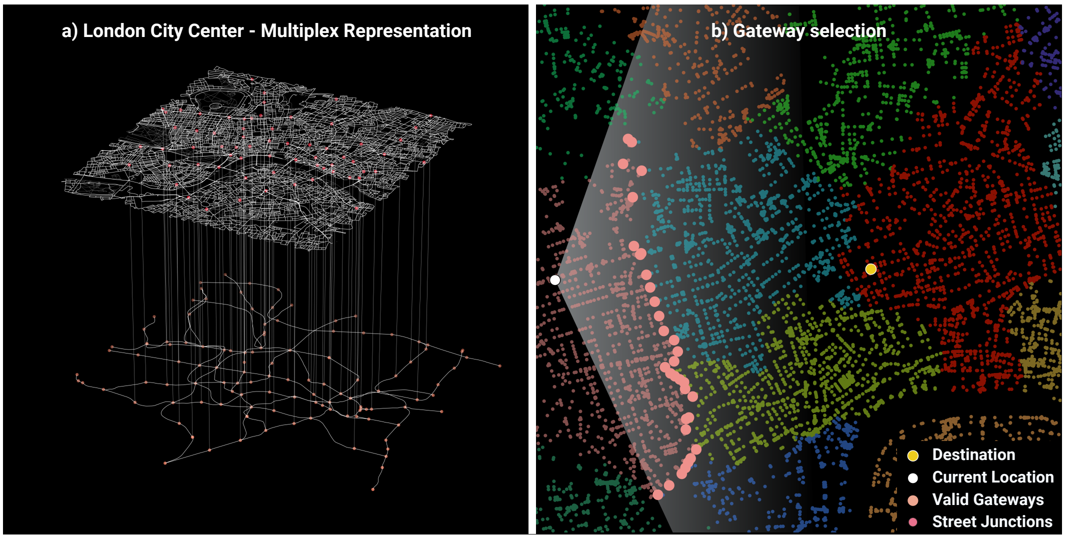

Figure 1 a) A multilayer-representation of the central area of London, UK: transit (below) and street (above) networks. b) Identification of possible gateways based on the location and the final destination of the agent.

The *modularity optimisation* algorithm [2] is employed to identify functional regions from the street layout. This algorithm is a community detection technique which optimises modularity, namely the robustness of a possible division in communities of a network. The community membership of the street segments is derived from topological ties existing in a dual graph representation, namely a graph wherein nodes represent street segments, links represent connections amongst them. Afterwards, each street junction is assigned to its region.

Modelling route-choice behaviour

To begin with, when a trip is formulated, the origin and destination nodes are randomly chosen with a probability based on their betweenness centrality value, i.e. the betweenness centrality values are linearly re-scaled to probabilities, such that the node with the highest betweenness centrality has the highest probability to be selected as an origin or destination. Furthermore, the destination is picked drawing from nodes located outside the origin's region.

The route-choice approach adopted here [13] follows the hierarchical structure in which the urban environment is decomposed: the agents' decisions shift from the regional- to the street-level. In other words, it is assumed that a walker, before conceiving a detailed street-segment path, decides upon a sequence of regions to traverse to reach the destination. At this initial stage, the algorithm moves from one region to another until the destination region is found. The selection of each next region is performed making use of *gateways*, namely pairs of *exit* and *entry* nodes located at boundaries between regions. Such gateways are roughly evaluated every time a new region is entered on the basis of the following rules [13]:

- The Euclidean distance between the *destination* and the possible exit node must be shorter than the distance separating the *current location* from the destination node.
- The exit node should be in the direction of the destination node: the angle formed by the current location and the possible exit is supposed to be between the one formed by the current location and the destination $\pm\alpha$ degrees on each side. In this work, we subjectively set the α parameter to 70°, instead of 90° as in [13], to coerce the agent to exclude gateways with a high deviation from the destination, assuming that pedestrians are less inclined to take large detours compared to drivers (see figure 1 b).
- The *entry node* belonging to the next possible region should be in the direction of the destination as well.

The current location either corresponds to the origin of the route, or, across the computation, to an entry node. In a nutshell, such criteria constrain the gateway selection process to candidates that are towards the destination region, relative to the position of the agent. When multiple choices satisfy the minimum requirements, the gateway with the lowest deviation from the destination is selected. The search process moves to the next region until the destination region is reached.

At the street decision level, the agent formulates a more precise path, selecting nodes between each pair of gateways. Decisions are based on an intra-region cost-minimisation approach. Angular change minimisation is used as a criterion [18] for its ability to predict peoples' movement and account for cognitive heuristics. The series of regional-nodes are merged and the complete path is generated. Figure 2 presents a summary of the steps described above within the ABM environment.

The case study

London (UK) is chosen as a case study. The road network and the urban railway network (Underground, Overground and Docklands Light Railway lines) are used to generate the multilayer representation. In each ABM scenario, agents are set to perform 1000 trips across the city, between pairs of OD separated by a maximum distance of 4000 meters.

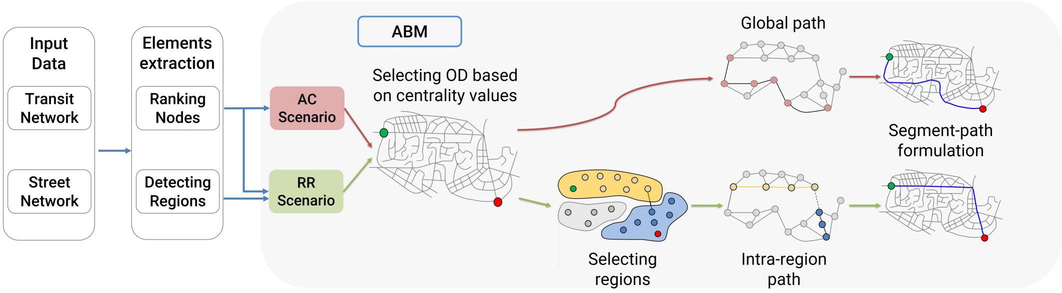

Figure 2 Summary of the methodology steps: nodes and paths between origin (red) and destination (green) are coloured in yellow, blue (RC scenario) or light red (AC scenario); graphics adapted from [13].

During the simulation, every single street segment records the number of times that it is traversed by an agent. In order to account for the randomness introduced by the selection of OD pairs, the scenarios are executed ten times; the mean of the flow of pedestrians across the different runs is calculated per segment and used thereby to compare the macro-level patterns emerging from the AC and RR scenario.

3 Results

The angular change shortest-path appears to bring about a low spatial variability of pedestrian segment usage across the case-study area (see figure 3). Most of the agents in this scenario made use of major roads to reach the city centre from the outer districts or vice versa. The A201 artery (including Farringdon Road and Blackfriars Bridge), in particular, was often traversed and emerged as the main link between the south and the north (some segments go to a maximum of 2400 crossings), from Elephant and Castle up to King's Cross. Likewise, the A40, along with the north bank of the Thames, was used to move from west to east. Many street segments were never crossed by the agents in this scenario (see figure 3 and 4).

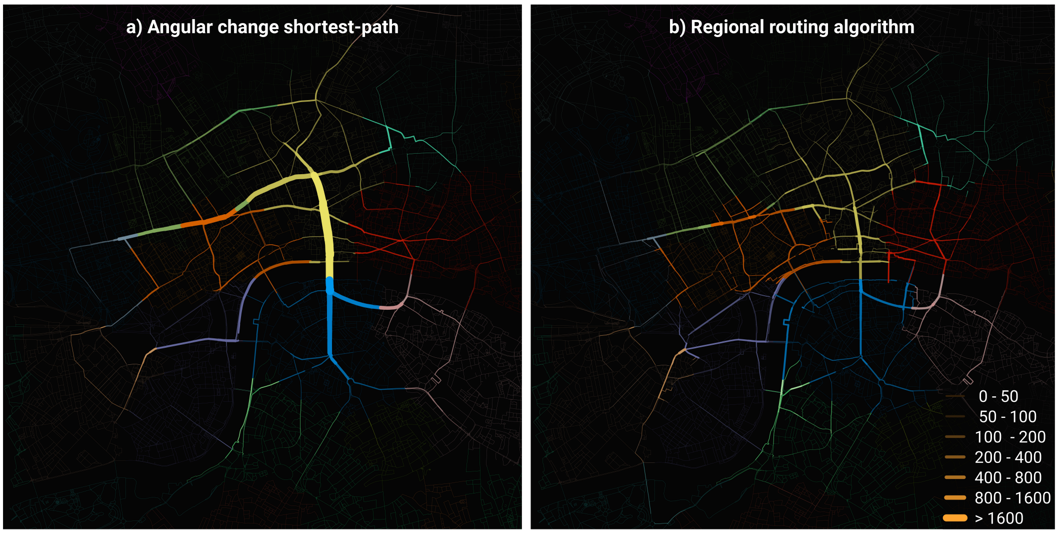

Figure 3 Street segments usage for 1000 trips in the ABM scenarios. Street segments are coloured by district membership; brightness and width indicate the number of agents' crossings.

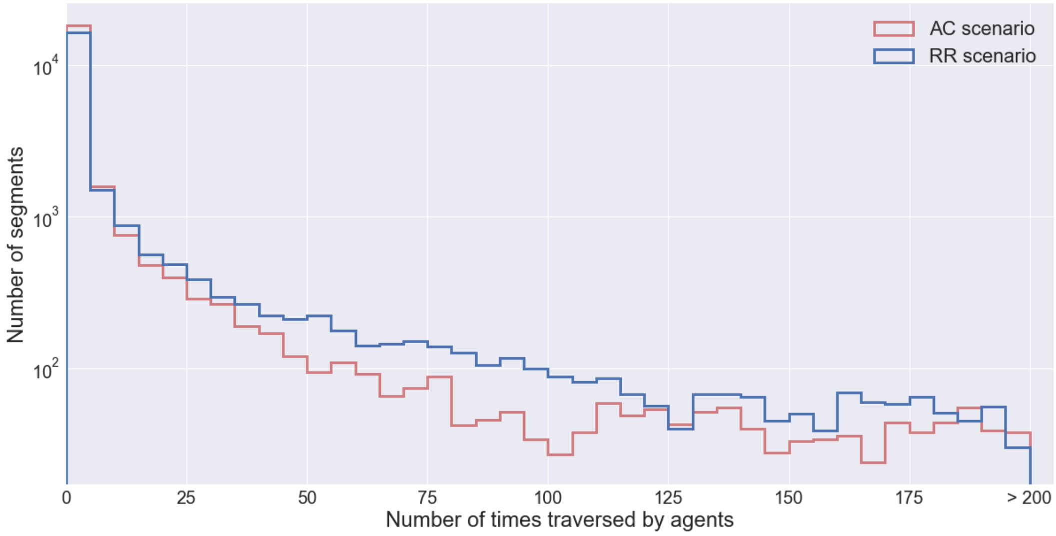

Figure 4 Frequency distribution of pedestrian density values across street segment features in the two scenarios.

Even though the A201 played a big part in the RR scenario as well, the agents exploited a wider range of minor roads to reach their destinations, leading to a more diversified pattern. The central districts, coloured in orange and yellow, exhibit a higher number of street segments with relatively high agents densities: 545 street segments were crossed more than 200 times in the RR scenario, against 434 in the AC scenario. The district coloured in red, although displaying a quite defined pattern, was traversed slightly more regularly by agents in the RR scenario (168 and 145 segments respectively above 200 counts); as a link between the north and the south, street segments in this region were probably used as an alternative to the A201. Indeed, in the RR scenario, along this road, the highest number of crossing is between 800 and 1000, almost 60% less in comparison with the AC scenario. The South Bank (blue district) shows a higher spatial variability, in contrast to the other scenario. Visible paths along the southern riverfront even emerge towards the east, probably as a result of the recourse to the Millennium and the Southwark Bridges (coloured in red), nearly invisible in the routes of agents in the AC scenario.

Figure 4 summarises these observations: while the AC scenario displays a larger number of segments that were rarely or not even traversed, the RR scenario presents higher frequencies at almost each crossing category higher than 10. At the same time, the AC scenario also presents a higher number of segments crossed more than 200 times, further suggesting a more extreme distribution of the flows. Out of 1335946 kilometres of street network, considering an average distance per journey of 1648 (RR) and 1529 (AC) meters, 58095 km of street segments were featured by more than 200 crossings in RR, 49400 km in the AC scenario. 1047528 km were crossed at least once in the RR scenario, 977006 km in the AC scenario.

On the whole, the south and the central areas are the ones where most differences between the scenarios arise. Generally speaking, the outer regions of the case-study area are less traversed. This may be attributable to an edge-effect deriving from the centrality computation. The central-eastern part of the city seems to be the most preferred in both conditions, whereas the north-western street segments of the city centre do not exhibit relevant differences between the scenarios.

4 Discussion

When compared to a single-level cost-minimisation scenario, the results of the regional routing scenario seem more plausible both at the agent- and the macro-level. Regional routing led agents to take advantage of different streets and diversify routes, believably in relation to the gateways' positions. By travelling across alternative paths to major roads, regional routing agents spread out through the street network and determined more balanced flow patterns. Moreover, at the micro-level, the spatial constraints introduced by the morphological structure of the regions and their reciprocal connections reduced behavioural uniformity amongst agents.

In light of these preliminary results, the methodology here presented could be further developed, at different levels. The node hierarchy employed to manipulate the selection of OD pairs could be adapted to prevent agents to wander primarily in the central area, almost avoiding segments along the case-study boundaries. Concerning districts, the selection of gateways could be better tuned by taking into account the cognitive salience of nodes. Furthermore, individual differences between agents can be explicitly included in the simulation, assuming that urban explorers traverse specific junctions based on their knowledge of the environment. Finally, a validation of the ABM with observational-data could provide insights regarding the performance of the model and/or the routing algorithm. Such step will be carried out in the next phases of the model's development by comparing the distribution of pedestrian across the street networks, per each segment, with densities obtained by pedestrian GPS trajectory data.

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