The ODD of PedSimCity

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PURPOSE AND PATTERNS

The purpose of *PedSimCity* is to simulate the movement of pedestrians across large urban areas. PedSimCity has been developed with the aim to accommodate empirical findings and theories on the role of *cognitive maps* – spatial mental models of the external environment – in spatial behaviour in an Agent-Based Model (ABM) of pedestrian movement in cities. The knowledge regarding meaningful urban elements stored in people's cognitive maps has proven to shape route choice behaviour, a set of behavioural and cognitive processes that refer to the formulation (and further situated readjustments) of a route between an origin and a destination. Yet, no ABMs for the simulation of pedestrian movement in cities incorporate a representational component in the design of the agents. Three sub-models are included in PedSimCity.

1. Testing Landmarks and 2. Testing Urban Subdivisions

These two sub-models address research questions related to the inclusion of cognitive maps in the behavioural architecture of the agents:

- How can cognitive maps and human spatial behaviour be incorporated into agent-based models of pedestrian movement in cities?
- To what extent does enhancing the complexity of the agents' cognitive representational capabilities increase the power of pedestrian movement simulation models to generate realistic pedestrian patterns?

We follow the *docking* framework described by Axtell et al. (1996) whereby two models - a benchmark simple one and a model with added complexity - are aligned to assess the differences (Sun, 2005) brought by the more complex model. The sub-models are built following a step-wise approach[1] to assess how the inclusion of certain meaningful urban elements in the cognitive map of the agents generates different, more plausible micro-, meso-, and macro-level patterns (see below) as compared to the ones generated by cost-based scenarios. In this sense, we distinguish:

- *Cost-based* scenarios (benchmark models), populated with agents who only employ road costs to generate their route (i.e. road distance and cumulative angular change - a measure of change of direction).
- *Elements-based* scenarios (complex models), populated with agents enriched with knowledge about certain urban elements.

Testing landmarks. The inclusion of *landmarks* (on-route marks and distant landmarks) in the agents' cognitive map is assessed against more traditional agent conceptions. The scenarios are: local and global landmarks + road distance minimisation, local and global landmarks + cumulative angular change, road distance minimisation only, cumulative angular change only, local landmarks + road distance, distant landmarks only. For details, see Filomena and Verstegen (2021). *Testing urban subdivisions.* The inclusion of *regions* and *barriers* in the agent's cognitive map is assessed separately and in combination, against more traditional agent conceptions. The scenarios are regions + cumulative angular change, barriers + cumulative angular change, regions + barriers + cumulative angular change, cumulative angular change. For details, see Filomena et al. (2020).

3. Empirical ABM

PedSimCity also includes a third sub-model where the urban elements are all included in the agents' cognitive map, but not necessarily used. The role of such elements and their interaction, also in combination with the road costs, is calibrated on the basis of empirical data collected through a qualitative study on walking and route choice behaviour. This model addresses the following research question:

- To what degree does the incorporation of empirical data into an ABM for pedestrian movement simulation produce different and more plausible meso-level patterns (distribution of pedestrians) compared to an uninformed model? Is the data collection effort justified?

[1]The urban elements are introduced separately one by one before deeming them "necessary".

The *Empirical ABM* contains three configurations. In the first one, the *null configuration*, the interaction between urban elements and road costs across the route formulation process is regulated by parameters whose values are drawn from uniform distributions. The parameter values of an agent in the *homogeneous configuration* are obtained from distributions built on the attributes observed in the sample of the empirical study. Finally, in the *heterogeneous configuration*, agent typologies are derived from clusters built from the attributes observed in the sample. The parameter values of an agent are obtained from distributions built on the attributes of the corresponding cluster of individuals. For details, see Filomena et al. (2022).

The ABM Patterns

The patterns that are used to evaluate and assess the components of the sub-models and the sub-models as a whole refer to a) *micro-*, b) *meso-* and c) *macro-level* patterns. Micro-level patterns refer to the subjective examination of individual routes. Meso-level patterns represent the volumes of the pedestrian agents recorded per each street segment, at the end of each run (e.g. the volumes of agents that crossed a certain street segment, in each of the scenarios). Finally, macro-level patterns refer to average characteristics of the routes formulated across a certain scenario or configuration (e.g. average length, number of meaningful elements encountered, number of junctions crossed, "landmarkness" of the route). Meso- and macro-level patterns can be obtained and analysed following these steps:

1. Running the ABM as a Monte Carlo simulation (e.g. 10 runs of the model).
2. Computing median values per street segments across the 10 runs, for each of the ABM scenario/configurations (e.g. landmark-based + road distance *vs* road distance minimisation scenarios).
3. Computing median values for the characteristics/attributes of the routes generated across the runs within each scenario/configuration.

ENTITIES, STATE VARIABLES, AND SCALES

An *agent* in the model represents a pedestrian. An agent is featured by a set of variables the regulate its basic movement across the *environment*. In addition, an agent has attached a set of properties *agentProperties* that define its route choice behaviour, see table 1. Agents are an entity for all the three sub-models. The empirical ABM sub-model includes an agent entity featured by the variables above and further properties included in the *EmpiricalAgentProperties* class; it also presents the *EmpiricalAgentGroup* entity to which agents belong to, see table 2. These groups are the agent typologies described above.

The *environment* is characterised by a set of geographical layers, see table 3:

- A graph representation of the *street network*, including *nodes* and *edges*.
- A set of *buildings*.
- Natural and artificial *barriers*.
- *Regions*, or districts; regions is formalised on the basis of membership of edges ad nodes.

Each agent is also equipped with a *cognitive map*, see table 4. At this stage of the model the cognitive map of each agent refers to a *community cognitive map*, shared across the agent population. While all the agents essentially make use of the same community cognitive map, they may use elements differently because of their characteristics (in the empiricalABM sub-model) or because of stochasticity. The community cognitive map includes information about the *environment*. *Global landmarks* and *local landmarks* are defined on the basis of general parameters from the set of buildings (e.g. local landmarks are buildings whose salience score is higher than 0.3, etc.). Local landmarks may be used as on-route marks, global landmarks may be considered as orienting distant landmarks when their location anchors the destination (i.e. when they are in proximity of the agent's destination).

Agents can change locations along the street network while they walk. At the end of a route, they can be moved to a new origin node. One step in the simulation is equal to 10 minutes and the moving rate of the age is computed considering that in reality the average pedestrian speed is around 1.42 metres per second. The environment components are not subject to changes across the simulation, although agents may perceive some of the attributes associated with the environment differently. The geographical layers are projected and their spatial unit is meter.

Table 1. The *Agent* entity and its variables

Variable Name	Description
Agent Class	
agentID	Unique identifier for the agent
OD	List of Origin-Destination pairs assigned to the agent
originNode	Starting node for the current agent's route
destinationNode	Destination node for the current agent's route
directedEdgesSequence	Sequence of directed edges to be walked by the agent
edgeIDsSequence	Sequence of edgeIDs to be walked by the agent
reachedDestination	Flag indicating whether the agent has reached its destination
tripsDone	Counter for the number of trips completed by the agent
agentLocation	Geometric representation of the agent's location
speed	Speed of the agent's movement
currentEdge	The edge the agent is currently traversing
startIndex	Starting index for the agent's current movement, along the current segment
currentIndex	Current index of the agent's movement, along the current segment
endIndex	End index for the agent's current movement, along the current segment
indexOnEdgesSequence	Index of the directed edge in the sequence
indexedSegment	The Indexed line of the current segment
pathDirection	Direction of the path
linkDirection	Direction of movement along the current edge
route	Route information for the agent's path
killAgent	Stoppable reference for the agent.
AgentProperties Class (Extends *Agent*)	
routeChoice	The agent route choice model
onlyMinimising	Only minimising road-based cost (distance or angular)
minimisingDistance	Only minimising road distance
minimisingAngular	Only minimising cumulative angular change
localHeuristicDistance	Using road distance as a local heuristic
localHeuristicAngular	Using angular change as a local heuristic
usingLocalLandmarks	Using local landmarks
usingDistantLandmarks	Using distant landmarks
regionBasedNavigation	Using region-based navigation
barrierBasedNavigation	Using barrier-based navigation
preferenceNaturalBarriers	Flag for preference for walking along natural barriers
aversionSeveringBarriers	Flag for avoidance of severing barriers
naturalBarriers	Mean for creating a distribution for the natural barrier effect
naturalBarriersSD	Standard Deviation for creating a distribution for the natural barrier effect
severingBarriers	Mean for creating a distribution for the severing barrier effect
severingBarriersSD	Standard Deviation for creating a distribution for the severing barrier effect
barrierType	Type of barrier that could be used as sub-goals (all, positive, negative, separating)
landmarkType	Type of landmarks for navigation (local vs global)

PROCESS OVERVIEW AND SCHEDULING

The ABM can be started through an applet or executed without interface. The interface allows choosing a sub-model to run and varying optional parameters through the applet. Once a sub-model has been chosen, jobs, number of agents, number of trips per agents, and alike parameters are defined automatically based on the sub-model; other simulation parameters can be modified by the user through the interface (e.g. parameters regulating the interaction between landmarks and road costs, thresholds, etc.). Contrarily, running the model without interface would require additional steps for configuring the ABM in *Eclipse* or similar IDEs as a Java Project. Thereafter, main and optional parameters would need to be set manually in the *Parameters* class.

At the start of the sub-model, the environment geographical layers are loaded and the environment is created. At that point the model is executed for a certain number of jobs. The ABM jobs can be executed in parallel or sequentially. For each job, when the schedule starts, the simulation is populated with the agents and their Origin-Destination (OD) pairs matrix.For sub-models 1. and 2. the scenarios are defined so that one agent represents one route-choice model (element-based or cost-based, see above). The agent is assigned with the number of trips and its corresponding routing mechanisms. Sub-model 3., instead initiates three configurations with a certain number of agents; they exactly correspond to the number of individuals in the empirical study sample. In the heterogeneous configurations, agent typologies are built on the basis of the clusters compositions. While in sub-models 1. and 2. the agents do not change their route choice behaviour, in sub-model 3. they do.

Table 2. The *Agent* entity and its *EmpiricalAgentProperties*

Variable Name	Description
EmpiricalAgentProperties Class	
groupName	The name of the group the agent belongs To
group	Group
usingElements	Using urban elements in the route choice behaviour
elementsActivated	Element-based navigation is enabled
elementsProbability	Probabilities of using or not element-based navigation
minimisationProbability	Probabilities for minimisation-only route choice models
localHeuristicsProbability	Probabilities for local heuristics
regionBasedProbability	Probabilities for region-based navigation
subGoalsProbability	Probabilities for using sub-goals in navigation
distantLandmarksProbability	Probabilities for distant landmarks
elementsMap	Map for element-based route choice models and probabilities
minimisationMap	Map for minimisation-only route choice models and probabilities
localHeuristicsMap	Map for local heuristics and their probabilities
regionBasedMap	Map for region-based navigation and its probability
subGoalsMap	Map for sub-goals and their probabilities
distantLandmarksMap	Map for distant landmarks and their probabilities
randomElementsMap	Map for random route elements and their probabilities
elements	Properties related to the using or not element-based navigation
minimisation	Properties related to minimisation-only models
localHeuristics	Properties related to local heuristics
subGoals	Properties related to the usage of sub-goals
regionBased	Properties related to using or not region-based navigation
distantLandmarks	Properties related to using or not distant landmark navigation
randomElements	Properties that could be randomly drawn when using elements, if not activated
EmpiricalAgentGroup Class	
groupName	Group name associated with the agent's properties.
share	Share value associated with the group.
probabilityRoadDistance	Probability for road distance minimisation approach.
probabilityRoadDistanceSD	Standard deviation for road distance probability.
probabilityAngularChange	Probability for angular change minimisation approach
probabilityAngularChangeSD	Standard deviation for angular change probability.
probabilityNotUsingElements	Probability for not using route choice elements.
probabilityNotUsingElementsSD	Standard deviation for not using elements probability.
probabilityUsingElements	Probability for using route choice elements.
probabilityUsingElementsSD	Standard deviation for using elements probability.
probabilityLocalRoadDistance	Probability for local road distance minimisation.
probabilityLocalRoadDistanceSD	Standard deviation for local road distance probability.
probabilityLocalAngularChange	Probability for local angular change minimisation.
probabilityLocalAngularChangeSD	Standard deviation for local angular change probability.
probabilityRegionBasedNavigation	Probability for region-based navigation
probabilityRegionBasedNavigationSD	Standard deviation for region-based navigation probability
probabilityLocalLandmarks	Probability for using local landmarks.
probabilityLocalLandmarksSD	Standard deviation for local landmarks probability.
probabilityBarrierSubGoals	Probability for barrier sub-goals.
probabilityBarrierSubGoalsSD	Standard deviation for barrier sub-goals probability.
probabilityDistantLandmarks	Probability for using distant landmarks.
probabilityDistantLandmarksSD	Standard deviation for distant landmarks probability.
naturalBarriers	Natural barriers value.
naturalBarriersSD	Standard deviation for natural barriers
severingBarriers	Severing barriers value
severingBarriersSD	Standard deviation for severing barriers

Table 3. *PedSimCity* environment variables

Variable Name	Description
roads	Geographical layer of the road segments
junctions	Geographical layer of the road junctions
intersectionsDual	Geographical layer of the dual road intersections
centroids	Geographical layer of the dual road centroids
buildings	Buildings in the case study area
barriers	Natural and artificial elements considered as barriers
sightLines	Lines of sight from nodes to global landmarks
network	Graph representation of the street network
dualNetwork	Dual graph represention of the street network.
buildingsMap	Maps IDs to building entities.
regionsMap	Maps IDs to region entities.
barriersMap	Maps IDs to barrier entities.
gatewaysMap	Maps pairs of nodes to gateway entities.
nodesMap	Maps node IDs to node entities.
edgesMap	Maps edge IDs to edge entities.
centroidsMap	Maps centroids' IDs to centroid entities.
distances	Stores a list of distances (testingLandmarks only), used for validation
startingNodes	List of starting nodes for generating OD matrixes (testingUrbanSubdivisions only)
currentJob	Represents the current job identifier.
flowHandler	Manages the collection of data regarding the distribution of pedestrians across the street network
empiricalGroups	List of empirical agent roups.
MBR	Represents the minimum bounding rectangle of the geographical layers of the ABM
agents	Geographical layer of the agents' locations
agentsList	List of agents

Table 4. The Community *cognitiveMap* variables

Variable Name	Description
localLandmarks	Geographical layer of the local landmarks included in the cognitive map.
globalLandmarks	Geographical layer of the global landmarks included in the cognitive map.
gatewaysMap	Maps pairs of nodes to gateways using a HashMap.
barriers	Geographical layer of the barriers included in the cognitive map.

For all the sub-model, at each step:

- If the agent has not retrieved an OD pair yet or has reached its destination:
  1. If the agent has terminated a trip, it updates the number of trips completed.
  2. The agent retrieves a new OD pair.
  3. It updates its location on the origin.
  4. *(Only empirical ABM, sub-model 3.)* On the basis of the agent parameter values (representing likelihoods/chances of adopting a specific behaviour), the route choice behaviour of the agent is shaped (e.g. reliance on different urban elements or road-costs is activated or not).
  5. The agent formulates the route for the OD (a sequence of edges that are supposed to be walked), on the basis of its variables and characteristics.
- If the agent has not yet reached a destination, it updates its position along the edges that it supposed to walk on the basis of the moving rate.

For every agent trip, the route is stored and the volumes of the edges composing the route are updated. The number of agents per street segments, at this developmental stage, does not influence the agents' decision making processes. Therefore, volumes are not updated on the fly but only stored for determining the patterns of the ABM. When an agent has completed all the trips it was assigned with, it is killed and removed from the list of the "active" agents. Once the list of the agents in a simulation is empty, the corresponding job is finished and the results are passed to the main handler.

DESIGN CONCEPTS

Basic Principles

The model design is rooted in cognitive mapping theories and empirical findings emerged in the last decades across cognitive geography, spatial cognition and, more recently, neuropsychology research (see the papers accompanying the model mentioned above, for details and references). The meaningful urban elements represented in people's cognitive map of the environment are said to influence route choice behaviour, a set of processes that takes place when pedestrians formulate their route (*prospective planning*), and when they reshape it while walking (*situated planning*). The ABM is an attempt to enhance how pedestrian dynamics are modelled, as compared to other prevalent models, by accommodating cognitive maps in the agent behavioural architecture.

In the model, at the computational level, both the prospective planning and situated planning phases take place before the agent is scheduled to walk; however, 2d and 3d visibility, the role of on-route landmarks and how they shape routes, for instance, are meant to reproduce processes that would normally take place along the route. The operationalisation of the role of the different urban elements represented in the agents' cognitive map has been driven by empirical findings for each of the elements discussed, along with the original definitions of these elements advanced by Kevin Lynch and colleagues. However, such an operationalisation is novel for what concerns both the individual incorporation of the elements in route choice model and their interaction in route choice models[2] Similarly, the usage of empirical data to directly characterise route choice models in urban space was unprecedented.

Emergence

The model verifies whether these basic principles - route choice models based on the role of the urban elements - produces micro-, meso-, and macro-level patterns that are a) different, b) more plausible as compared to rout choice models exclusively based on the minimisation of road costs. It also intends to shed theoretical light on the interplay between these elements, the relationship between urban structure, cognitive maps, and movement flows. The model allows verifying how the patterns emerging from the behaviour from the element-based scenarios differ across themselves and from the cost-based patterns. This is due to the fact that the role of the different urban elements was firstly investigated separately. The results, moreover, are not shaped by the OD matrix definition or other randomised processes as the ABM is run as a Monte Carlo Simulation for a certain number of runs; this number of runs was set by observing when the patterns would become stable.

Adaption and Sensing

Agents adapt their behaviour on the basis both of their behavioural rules or process and the characteristics of the environment. Element-based agents tend to minimise road-costs, while also reshaping their route on the basis of the structure of the environment in regions, a local landmark that suggests taking a turn, or because of the distribution of distant visible landmarks around possible destinations, for example. While agents tend to behave to some extent on the basis of objectives, some of their decision-making processes are rather structured following the hierarchical and ergonomic organisation of the spatial knowledge about the environment.

Objectives

- All the agents' objective is to reach their destination.
- Benchmark agents try to minimise road-costs (distance or angular change) for reaching their destination.
- All the element-based agents' objective is to minimise road costs locally, while making use of other navigational cues or strategies:
  - Some agents try to maximise the 3d visibility of distant landmarks around their destination, i.e. keeping them in sight while walking (sub-model 1).
  - Some agents identify on-route marks that help them facing the navigational complexity of the environment (sub-model 1).
  - Some agents reshape their route choice behaviour pushing themselves towards orienting barriers, i.e. rivers, parks, major roads (sub-model 2).
  - Some agents define a region-based global path before making use of road costs (sub-model 2).
  - Some agents may try to walk along attractive natural elements, others may avoid walking along major roads or unpleasant urban elements, other would tend to do both (sub-model 2).
- Empirical-based agents would be characterised by a mixture of the objectives above (sub-model 3).

[2] Only, the role of regions was already modelled in another ABM designed for modelling driving behaviours (Manley et al., 2015).

Learning, Prediction and Interaction

Agents do not learn and do not interact at this developmental stage. They are also not aware of the consequences of their actions.

Stochasticity

Stochasticity is used to model the definition of the OD matrix as well as the perception of road costs (agents are not able to exactly know how long a road segment is); in addition, in sub-model 3, the definition of the route choice behaviour of the agent is structured hierarchically through the prospective and situated planning phases. It entails different steps, regulated by stochastic discrete parameters. Furthermore, stochastic preference parameters direct the perception of costs of street segments located near barriers (see Filomena et al. (2022)).

Collectives

In sub-model 3, in the heterogeneous configuration, agents belong to different groups. However, agents are not aware they may belong to different groups.

Observation

The data used to evaluate the sub-models refer to:

- Volumes of pedestrian agents at the street-segment level, across the street network of the case study. Naturally, agents belonging to different scenarios or configurations (or groups) are distinguished to observe how they distribute themselves in different ways.
- The pedestrian agents' routes. These are saved after each run and they are used to assess the characteristics of the agents paths across the environment, in relatio to the corresponding routing mechanisms that generated them.

INITIALISATION

The number of entities depend on the sub-model, but usually, one agent per route choice model is initialised (sub-models 1. and 2.).

- Testing Landmarks, 6 scenarios, 1 agent per scenario, each completing 255 trips, as many as the a set of pedestrian observational routes used to validate the model.
- Testing Urban Subdivisions, 4 scenarios, 1 agent per scenario, each completing 2000 trips.
- Empirical ABM, 3 configurations, 301 agents, as many as the individuals in the sample of the empirical study, each completing 3 trips.

In all the sub-models, non-agent related parameters that regulate the generic usage of the urban elements do not change (e.g. weight of distant landmarks visibility and road costs, thresholds, etc) across the different runs, once the simulation has started. These are set by default but they can be changed by the user. Furthermore, the speed of the agents does not change across the simulation. While the street segments properties (e.g. their length or angular relationships) or other environment variables do not change as they depend on geometrical fixed properties, the agents' perception of these costs vary on the basis of stochastic parameters.

The agents in sub-model 1. and 2. are initialised with a fixed route choice model, depending on the characteristics of their cognitive map (e.g. they use on-route marks and distant landmarks while minimising angular change for all their trips). In the case of sub-model 1., the OD matrix is generated on the basis of a set of distances derived from the distances between the origin and the destination of the routes in the validation dataset. This is to facilitate the comparison between the routes generated by the model and the ones used to validate it.

In sub-model 3, the agents are initialised with average and standard deviation values so as to derive a distribution of values that would regulate the usage of different navigational strategies. While the distribution are created on the basis of empirical data (homogeneous and heterogeneous configuration) and their initialisation does not change, the resulting behavioural characteristics of the agents in these configuration may change across a single run.

INPUT DATA

All the data necessary to run the experiments associated with the sub-models are included in the applet. See also https://github.com/g-filomena/PedSimCity.

The data refer to the geographical layers of the case study cities necessary to create the ABM environment. The input data also includes:

- Sub-model 1.: A set of distances for the Testing Landmarks sub-model. This is used to derive the distances between the origin destination when generating the OD matrix.

- Sub-model 3.: The attributes of the clusters derived from the empirical study. These refers to the behaviour of the subjects and the attributes used to summarise and describe their route choice behaviour. This data is used to create agent typologies in the heterogeneous configuration and to inform the agent population in the homogeneous configuration.

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