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An agent-based pedestrian model considering spatial behavior parameters

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Abstract

Contemporary pedestrian volume models are constructed mainly according to the space syntax framework. However, although these models predict pedestrian volumes with a good deal of success, they do not account for the dynamics of the reciprocities observed between street networks, pedestrian movement and land-use patterns. In this paper we present an agent-based model for predicting pedestrian movement at the urban scale. Due to its dynamic dimension, this model can aid in examining pedestrian flows in different places with respect to the relevant street network structure and land-use distribution. The model suggested here is constructed from the main components of space syntax models and thus allows specification of relevant spatial behavior parameters for a given urban area through comparison of the aggregate simulated movement of individual agents with the pedestrian movement volumes observed. The model was implemented in two Israeli city centers in order to illustrate its potential in three domains: evaluation of pedestrian volumes in the network, enlightenment of the reciprocities between street networks, land uses and movement, and assistance in the urban design process.

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Keywords: pedestrian volume models; agent-based model; space syntax; urban dynamics; urban desigen

1. Introduction

Evaluation of pedestrian movement volume over the street network is essential for the planning and design of urban environments, especially in the creation and maintenance of livable city centers. However, as collection of pedestrian data in urban environments is unfeasible, pedestrian volume models have been constructed in its place. Previous studies divided pedestrian volume models into two main approaches, with each reflecting differences in the scale of application (Raford and Ragland, 2006): Network analysis models are applied to city-wide and neighborhood levels and micro-simulation or Agent-based models focus on single or a small number of streets,

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intersections, open spaces, or building interiors. This classification likewise reflects differences in the required inputs and the most frequent outcomes (e.g. Batty, 2001; Jiang and Gimblett, 2002; Torrens 2012).

The network analysis models at the urban scale were constructed mainly within the methodological framework of the space syntax approach (Hillier et al., 1993). However, although these models predict pedestrian volumes with a good deal of success (e.g., Desyllas et al., 2003; Omer et al., 2015), they do not account for the dynamics of the reciprocities observed between street networks, pedestrian movement and land-use patterns (Batty, 2001; Raford, 2010).

In this paper we present an agent-based model for predicting pedestrian movement at the urban scale. The model incorporates components of network-based space syntax models; hence, this model integrates in some sense the network analysis and agent-based modeling approaches. The model is essential to achieve a twofold aim: first, due to its dynamic dimension, to shed light on the complex reciprocities between street networks, land uses and pedestrian movement, and second, to assist in urban planning and design. Although space syntax methodologies can effectively enhance urban design process and strategic planning (Karimi, 2012), they exhibit difficulty in accounting for the implications of changes in the street network and land-use patterns on movement (Batty, 2001; Haklay et al., 2001; Shelton, 2012).

The agent-based model suggested here is constructed from the main components of space syntax models and thus allows specification of relevant spatial behavior parameters. The appropriate parameters for a given urban area are chosen through comparison of the aggregate simulated movement of individual agents with the pedestrian movement volumes observed.

The model was implemented in two Israeli city centers in order to illustrate its potential in three domains: evaluation of pedestrian volumes in the network, enlightenment of the reciprocities between street networks, land uses and movement, and assistance in the urban design process.

2. Methodology

2.1. Contemporary pedestrian volume models

The space syntax pedestrian volume models constructed for various cities have shown that the spatial distribution of pedestrian volume in the street network can be explained and predicted by the centrality level of a given axial or segment line (e.g. Hillier et al., 1993; Jiang, 2009). Most of the pedestrian volume models constructed in recent years have nonetheless combined space syntax variables with land use and socio-economic variables (Desyllas et al., 2003; Lerman et al., 2016; Omer, et al, 2015; Raford and Ragland, 2006).

When describing the centrality level in the street network structure, two types of space syntax centrality measures are computed – Integration and Choice – which correspond to the graph-based centrality measures Closeness and Betweenness, respectively. Integration represents a given street segment's accessibility within the network (i.e., its to-movement potential) while Choice represents the extent to which a street segment functions as an intermediate location within the network (i.e. its through-movement potential) (Jiang & Claramunt, 2004). The Integration and Choice measures can be calculated on a global level (by taking the entire axial or segment map into account), or on a local level, according to selected distance radii. When the analysis is based on a segment map, the radius can be defined in metric units (250, 500, 1,000 meters and so on). Studies that employed space syntax techniques to evaluate pedestrian movement volume found that cities as well as urban areas may differ in the radius (topologic or metric) for measuring centrality that best describes their particular movement distributions (Jiang, 2009; Omer et al., 2015). Cities can, in addition, also differ in the distance type used for measuring a street network’s centrality (Omer and Jiang, 2015).

Hence, the pedestrian volume models constructed for different cities and urban areas can be expected to differ in the centrality measures that best explain the distribution of movement flows in the network by: (i) type of centrality measures (to-movement or through-movement) or their combination; (ii) scale (radius) of measurement; and (iii) type of distance (topological, angular or metric) by which centrality measures are calculated.

These aspects of street network centralities, together with the weight of the different land-uses, need to be taken into consideration when constructing an agent-based model directed at estimating pedestrian movement in a given city or urban area.

2.2. Agent-based simulation

The model presented here was designed with the NetLogo (ver.5.0.5) environment (Wilensky 1999) and based on elementary models designed to investigate issues regarding the relationship between agents' travel behavior and aggregate movement flows (Jiang and Jia 2011; Omer and Jiang (2015). The agent-based simulation model was constructed by taking into consideration the main aspects of space syntax modeling, in this case, the travel behavior of moving agents as defined by two components:

(i) Distance type: Based on the centrality measures used in space syntax modeling, three types of agents were defined: the metric, the topological and the angular, each of whom chooses the shortest path – metric, topological, or angular, respectively – between origin-destination pairs.

(ii) Scale/radius for movement: Radius is defined as the maximum distance available for movement between origin-destination pairs. This distance is defined in the model according to a given metric radius. Based on the metric radii centrality measure computed in space syntax research (e.g. Hillier, 2012), the maximum range of distance for movement between origin-destination pairs is defined as the following metric radii – 250, 500, 750, 1000, 1250, 1500, 1750, 2000, 2500, 3000, 4000, 5000 m – for the entire urban area (radius n).

By choosing the shortest routes between an origin and a destination according to a given distance type and radius, agents actually determine the aggregate flow volume in each street segment. Hence, the actual distribution of aggregate flows formed by the simulated movement is equivalent to the Choice (Betweenness) centrality measure of the same distance and radius type.

Our model's setup is as follows: When destinations are designated in a given radius, agents are programmed to choose the shortest paths according their type. Once they reach their first destination, they choose their second destination and so forth. In each simulation iteration, the number of agents in each segment is measured by the 'gate count' method. In each simulation run of the 10k iterations in the network, we assigned 15 agents to each of the three agent types (a total of 45 agents). The parameters appropriate for the model of a given urban area were chosen through comparison of the aggregate simulated movement of agents comprising the observed pedestrian volume in selected street segments by means of NetLogo's "behavior space" method. This method enables exploration of the model's behavior space and determination of which combinations of settings best correlate with the observed movement. Table 1 presents the variables and parameter ranges examined in the behavior space. The different combinations were examined with a total of 640 model runs.

Table 1. Behavior space initialization: Variables and range (subsets of parameter values).

Variable	**Range**				
Radius (m)	500	1000	2000	3000	5000
Commercial center		0.8		1.0	
Commercial store		0.6		0.8	
Bank		0.7		0.9	
Education		0.3		0.6	
Public institutions		0.3		0.6	
Industrial		0.3		0.6	
Culture/ sport		0.3		0.6	

2.3. The case studies

The centers of two Israeli cities, Kfar Saba and Ashdod, were chosen as case studies for implementing the agent-based model. These areas differ in their street patterns, land use distribution and consequent interrelations (Figure 1). Kfar Saba, founded in 1912, developed mainly through continuous urban growth; it is characterized by a predominantly orthogonal street pattern, with retail activities concentrated in its central area. The city center evolved from the city's historical core, with retail activities generally concentrated within its boundaries. In contrast, Ashdod is a planned young city, established in 1956 according to a comprehensive city plan. The city is characterized by hierarchical street patterns and by residential neighborhoods designed according to the ’neighborhood unit’ model (Rofe and Omer, 2012), including its central area, the first to be built.

Data on the two cities` street networks (updated for 2011) were obtained as GIS layers from the firm Mapa. A segment map of each city’s street network (Figure 1) was created and analyzed (i.e. by computing the space syntax measures) using Depthmap software (version 10.14, UCL). Data on non-residential buildings were obtained from the Survey of Israel (MAPI) as a GIS point layer. The pedestrian data were collected by means of a count survey carried out in street segments representing a range of different centrality values (for details see: Omer et al., 2015). The data was analyzed in SPSS (ver. 22) and presented using ESRI`s ArcMap (ver. 10.3) GIS software. The distribution of the non-residential land uses and the ‘gates’ in the sites observed area are presented in Figure 1.

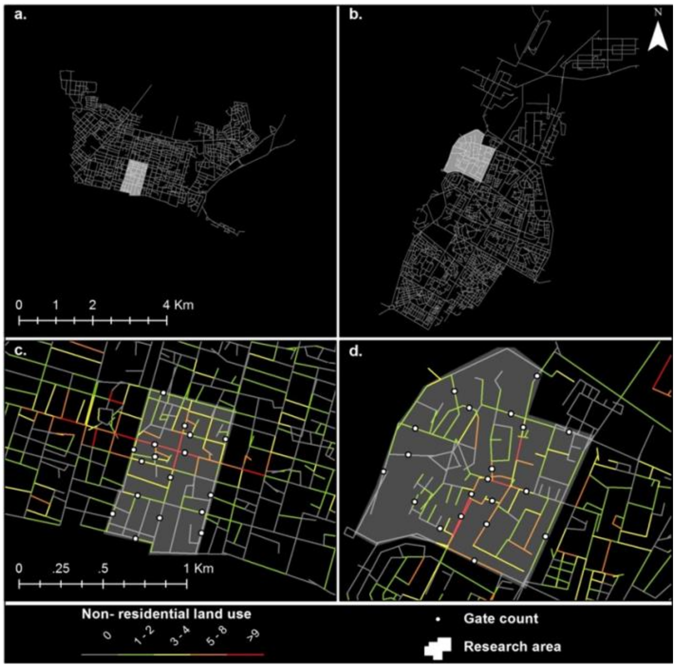

Figure1. Street segment maps of the study areas. The streets are visualized by spectral colors ranging from red (highest) to blue (lowest) according to the frequency of non-residential buildings found at the segment level. The "gates" are represented by white dots.

3. Results

3.1. Evaluating pedestrian volumes with the agent-based model

Table 3 presents the model's parameter space as revealed by the "behavior space" tool as well as the correlations between the agents' aggregate simulated movement and the observed pedestrian volumes for both study areas. It can be seen that the most prominent difference between the study areas is the radius of the centrality: in Kfar Saba the dominant radius is large in scale (5,000 meters), reflecting an urban scale, while in Ashdod the dominant radius is much smaller – a radius of 500 meters – reflecting a local scale. This difference is of course very important when considering the differences between city centers. Moreover, the appropriate or best (44.5%) models runs representing the aggregate movement flows in Kfar Saba were within a radius of 3,000 meters while in Ashdod the best (41%) models runs were within a radius of 1,000 meters or less.

Table 4 presents the variables, parameters and correlation coefficients of the multiple linear regressions (stepwise method) constructed for each study area according the space syntax methodology. In these regression analyses, the space syntax and the land-use variables are the independent variables whereas the observed pedestrian volume is the dependent variable. As in the case of the agent-based model, the scale of the space syntax centrality measure is much larger in Kfar Saba (radius> 5000 meters; city level) than in Ashdod, with the radii ranging between 250 and 1,250 meters by distance type.

Table 3. The study areas' parameter space, as measured by "behavior space" tool, with the framework of the agent-based model.

Variable	**Kfar Saba (city center)**	**Ashdod (city center)**
Radius (m)	5000	500
Commercial center	0.8	0.8
Commercial store	0.6	0.6
Bank	0.7	0.9
School	0.6	0.6
Public institution	0.3	0.3
Industrial area	0.3	0.6
Culture/ sport	0.3	0.3
R^2	0.920	0.838
Adjusted R^2	0.915	0.829

Table 4. The space syntax pedestrian model: Regression models for prediction of hourly pedestrian volumes on study area street segments.

Area	**Variables**	**B**	**β**	**t**
Kfar Saba (city center)	Topological choice (r>5000m)	0.001	0.813	12.243
	Commercial stores	27.207	0.238	3.582
R^2	0.963			
Adjusted R^2	0.958			
Ashdod (city center)	Angular integration (r1250 m)	0.014	1.027	8.311
	Commercial centers	0.159	0.284	3.716
	Metric mean depth (r4000 m)	0.003	0.343	3.560
	Angular choice (r250 m)	0.014	0.547	3.445
	Topological choice (r250 m)	-0.009	-0.471	-2.493
R^2	0.928			
Adjusted R^2	0.902			

Despite the differences between the space syntax model and the suggested agent-based model, their respective movement flows are quite similar in Ashdod (R2= 0.86) but especially in Kfar Saba (R2= 0.91), although they do reveal some differences. Figure 2 presents the differences between the simulated movement flows and the predicted movement flows according to the space syntax model. It can be seen that in the case of the simulated movement flow, the pedestrian volumes increase also in street segments located on the shortest paths that lead to these same segments. Because the relative locations of attractive land uses are taken into account it is possible that street segments with a low centrality level and no attractive land uses can enjoy high pedestrian movement volumes.

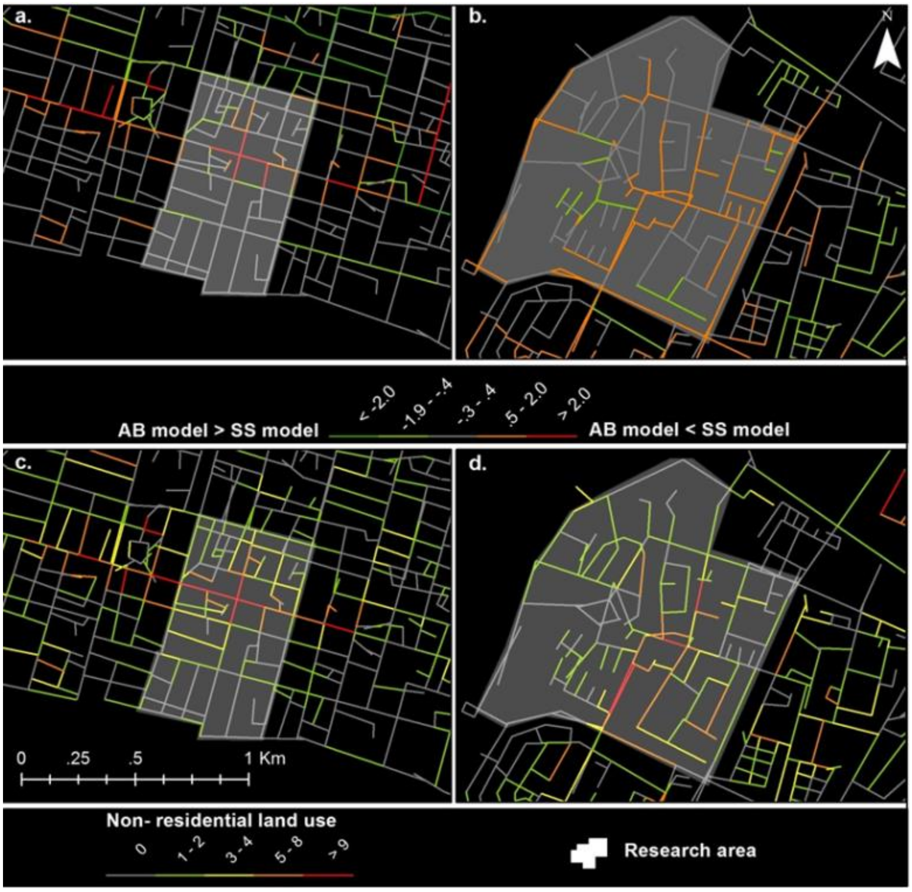

Figure 2. (a) Spatial distribution of z-score values obtained by liner regression of predicted movement flows according to the space syntax (SS) model and simulated movement flows according to the agent-based (AB) model in Kfar Saba (a) and Ashdod (b); Distribution of non-residential land uses in Kfar Saba (c) and Ashdod (d).

3.2. The model's potential to throw light on reciprocities between street networks, land uses and pedestrian movement

The correlations of the street network centrality measures across scales (different radii) with retail land-use patterns and observed pedestrian movement are presented in Figures 3.a and 3.b, respectively. The study areas differ in several aspects. The correspondence of the retail land use pattern with the aggregate movement flows in Kfar Saba are much higher at larger scales (radii), from radius 2,000 meter up to the city level (N), especially in relation to the topological-angular centralities. In contrast, the correspondence in Ashdod is relatively low across all the scales (radii), and tends to be lower at the larger scales, particularly with respect to the same centralities.

The differences between the study areas along these parameters are reflected in the correspondence between the scales (radii) of the centrality measures and the observed movement (Figure 3.b). While the correlations in Kfar Saba are higher at the larger scales, from radius 2,000 up to the city level (like the case of the correlations with retail patterns), in Ashdod the correlations are relatively higher at the local scales, up to the same radius of 2,000 meters.

Thus, the two city centers examined differ in the scale of their urban dynamics. In Kfar Saba it occurs at the large scales, mainly at the city scale, while in Ashdod it occurs at smaller scales, more or less at the local neighborhood level. In addition, Ashdod exhibits a greater correspondence between the components of these dynamics, that is, the street network, the land-use pattern and pedestrian movement. In addition, the actual overlap between the shortest routes of the various distance types is relatively lower in Ashdod's central. As we will show, counteracting this weakness is the main motivation behind the current urban planning projects for Ashdod.

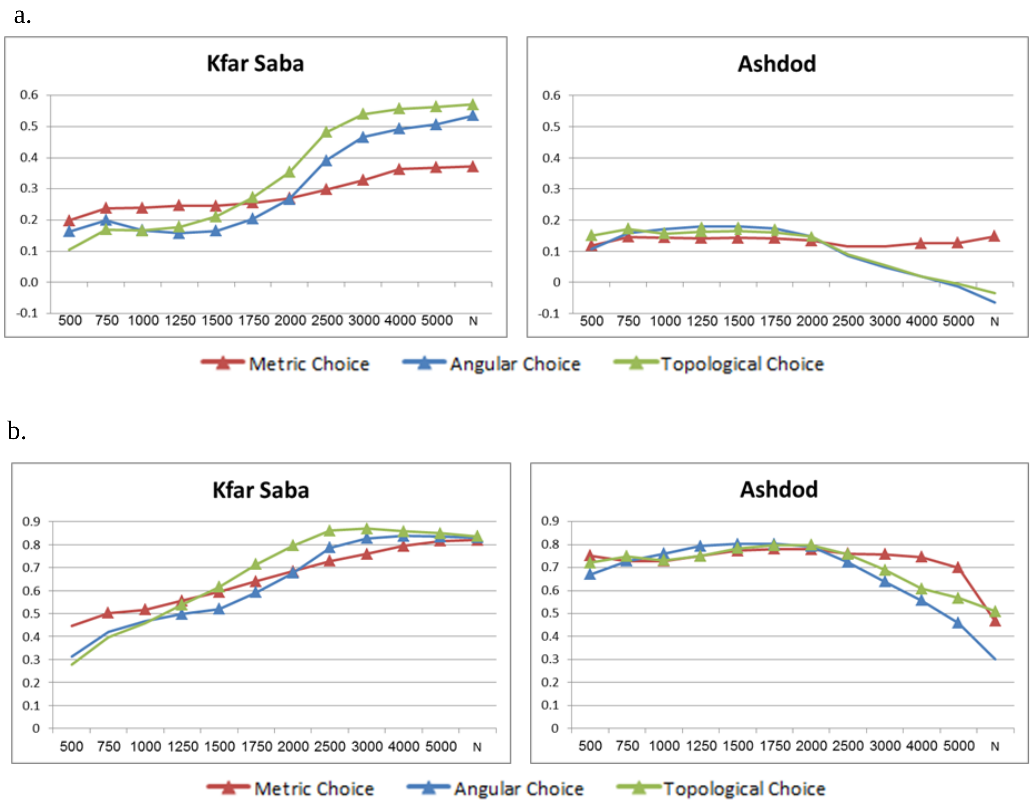

Figure 3. Correlations of centrality measures with retail (a) and observed movement (b). Only significant correlations ($p < 0.05$) are signed by symbol.

3.3. The model's potential to assist in urban design

The comparison between different types of city centers – as those found in Kfar Saba and Ashdod - illustrates the essential role of continuous and relatively self-organized urban growth in the formation of retail activities in the center while also revealing the weakness of the center in planned towns. The operative conclusion of the findings obtained in this study points to the necessity of creating conditions that will encourage formation of retail activity in Ashdod's central area, where the potential for through- and to-movement at the city level is high. Such conditions may stimulate improvement in accessibility to retail services, decrease the gap between accessibility and movement paths at large urban scales, and lead to the development of a more dominant and livable city center.

As the case of Kfar Saba’s city center shows, the scale of correspondence between a street network’s structure and retail activity is essential if a city center is to retain its strength and vitality. In the wake of this finding, the main objective of currently planned projects for Ashdod’s city center is to adjust the location of new retail activities to the network's main traffic routes or at least to a streets of higher centrality than currently observed.

Accordingly, in the agent-based simulation that was applied for Ashdod’s city center, new commercial centers and public institutions are added in the area to the main road with the higher potential for through- and to-movement at the city level (i.e. with the higher Integration and Choice centrality values) (Figure 4a-4b). The implications of these changes in the land use patterns (Figure 4c-4d) are more movement, not only in the main road but also in secondary roads, especially roads that lead directly to the main road.

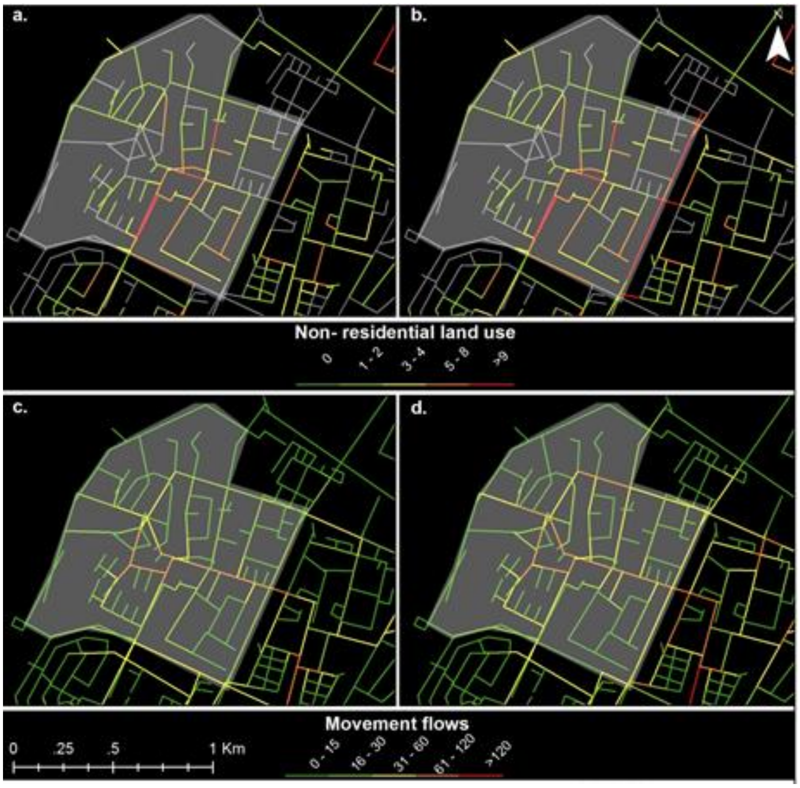

Figure 4. Non-residential land-uses before (a) and after (b) the changes; the simulated movement flows before (c) and after (d) changes in Ashdod's city center.

4. Discussion and Conclusions

We have presented in this paper an agent-based model for pedestrian movement at the urban level. The model's potential is illustrated and discussed with respect to three aspects: The ability to evaluate pedestrian movement volumes in the street network; the ability to throw light on the reciprocities between street networks, land uses and movement; and the ability to support the urban design process.

Implementation of the model in two city centers that differ in their morphological character and in the dominance of planning in their growth indicated that the model can contribute in the evaluation of pedestrian movement distributions. As a result of its explicit dynamics, the agent-based model can throw greater light on the relationship between street networks, land uses and pedestrian movement. The movements simulated in the study's two city centers illustrate how the spatial distribution of land-use patterns, together with that distribution's association with street network structure, are crucial for ensuring the sustainability of dynamic city centers. Based on the agent-based model's ability to capture pedestrian movement and evaluate pedestrian volumes as well as elucidate urban dynamics, we have shown its potential to contribute to the design process.

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