An agent-based model to explore urban policies, pedestrian behaviour and walkability

Georgios Tsaples*

University of Macedonia,
Egnatia Str. 156, 54636, Thessaloniki, Greece
Email: gtsaples@gmail.com
*Corresponding author

Giovanna Fancello

Université Paris Dauphine,
Place du Maréchal de Lattre de Tassigny,
75016 Paris, France
Email: giovanna.fancello@lamsade.dauphine.fr

Abstract: The purpose of this paper is to use the agent-based methodology both as a research tool to study pedestrian behaviour and as a decision support system for urban authorities aimed to improve walkability. The developed model represents an urban environment with its citizens/agents performing movements under different means of transport and towards different destinations. Different scenarios, demonstrated that by improving the conditions of the urban environment people walk more and a bigger part of the environment is considered as 'favourite for walking'. Moreover, the conduciveness to walk affects the daily peoples' behaviour, and acts also as a positive influence to economic activity.

Keywords: agent-based model; pedestrian behaviour; walkability; urban environment; decision support system; DSS.

Reference to this paper should be made as follows: Tsaples, G. and Fancello, G. (2018) 'An agent-based model to explore urban policies, pedestrian behaviour and walkability', *Int. J. Decision Support Systems*, Vol. 3, Nos. 1/2, pp.4–18.

Biographical notes: Georgios Tsaples graduated from the Aristoteleion University of Thessaloniki and received his MSc in Engineering and Policy Analysis from the Delft University of Technology, where he was introduced to simulation (especially system dynamics and agent-based modelling) and decision analysis (multi-criteria decision analysis). He worked as a Research Fellow at Center for Cyber Intelligence and Information Security of the University of Rome 'La Sapienza', where he was part of the System Dynamics Group and was working on EU-funded projects dealing with the simulation of disruptive events in urban transportation systems. He has collaborated with the University of Macedonia in Greece, where he used operational research and statistics techniques in EU-funded projects dealing with European societal issues such as racism in football, game-based teaching, etc.

Giovanna Fancello is a Postdoctoral Researcher in Aiding Decision at LAMSADE, Université Paris Dauphine, France. She holds a PhD in Architecture and Planning from the University of Sassari, Italy in 2014. She was a Postdoctoral Researcher in Urban Planning at the University of Sassari – DADU, Italy (2014–2015). Her research deals about urban and territorial planning, spatial multi-criteria evaluation for public decision making, decision analysis, aiding decision tools with GIS, urban quality of life, walkability and urban resilience.

1 Introduction

Pedestrian accessibility of the city is one of the main aims of the urban public policies, for this reason, it is receiving a growing attention among scholars and policy makers in the last years in scientific fields like medicine, social and environmental sciences, engineering, health professions, arts and humanities (Blečić et al., 2015; Cervero and Duncan, 2003; Clifton et al., 2007; Forsyth, 2015; Frank et al., 2006; Livi and Clifton, 2004; Páez, 2013; Porta and Renne, 2005). The accessibility to the city and its opportunities by pedestrians concerns not only the transportation idea (Hansen, 1959) of distances and affordance of urban services and activities. Moreover, it deals with a multidimensional and more complex concept, the walk-ability, dealing with the real possibility (ability) citizens have, to reach and use the urban space, considering all the relations and interactions among pedestrians, urban space and the social practices (Harvey, 2003; Lefebvre, 1996; Lynch, 1960, 1981; Jacobs, 1961).

However, rarely more dynamic methods are used with the aim of analysing and estimating the processes that influence the behaviour of individuals in space and in time, as a multi-agent model can do.

The present paper utilised the methodology of agent-based modelling (ABM) to simulate an urban environment with the movement of citizens and the use of various means of transportation. ABM is a computational technique that is focused on explaining complex systems in terms of agents and their interactions. The methodology of ABM encodes the agents and their interactions in simple rules, which allow us to observe the results of those interactions.

An agent can be defined as an autonomous computational item, person or object of a system with particular properties/attributes and actions that are encoded into simple decision rules. The properties of an agent describe its state (Wilensky and Rand, 2015). On the other hand, an agent's actions are what the particular agent can do, meaning what are the decision rules that allow the agent to interact with:

- other agents
- itself
- the environment.

ABM has several advantages over other modelling techniques that can be summarised in the following:

- Agents and their interaction are easier to understand because
  - a Humans naturally think in terms of interactions and agents
  - b We can project our own experiences to the agents
  - c The real world is more closely matched to an AB Model
- ABM can model systems of heterogeneous components, whereas computational models make assumptions of homogeneity
- ABM does not require knowledge of aggregate phenomena
- The results of ABM are more detailed
- It is easier to incorporate randomness (Wilensky and Rand, 2015).

Hence, the purpose of the model is twofold: to use simulation with the purpose of investigating how the choice of transportation by people can affect the urban environment both in the short- and long-term. Second, how the urban environment can affect the behaviour of people especially with regards to walking. Furthermore, the model can be of help to decision-makers as a learning tool with the aim of testing policies in a consequence-free environment, policies that can help urban environments/cities transition more smoothly to a state of sustainability.

The paper is structured as follows: in the next section there is a short description of the main issues regarding urban walkability and how these notions have been used under the agent-based modelling approach. In addition, there is a description of the ABM model and its main characteristics. In Section 3, the main results of the model are presented while conclusions, and directions of future research are presented in the final part.

2 State-of-the-art in ABM and walkability models

Numerous researches aim to reveal and analyse the factors that influence the relationships between individuals and space. These are factors related to the quality of the built environment and its propensity to be walked and its capacity to foster the pedestrian mobility in everyday life influencing people's quality of life, health and behaviour (Blečić et al., 2015; Ewing and Handy, 2009; Porta and Renne, 2005). Some of these studies seek to unveil how the built environment and its configuration influences people's choice to travel for work, leisure or for active transportation (Clifton et al., 2007; Ewing and Cervero, 2001; Forsyth et al., 2008; Hajna et al., 2013; Iacono et al., 2010; Kelly et al., 2011; Lee and Moudon, 2006; Owen et al., 2007). Others stand out for exploring the subjective differences among people with respect to their values, preferences and characteristics that affect their behaviour (Handy and Niemeier, 1997). Moreover, many studies claim a relation among walkability and quality of life and health. For them, walkability is considered as a fundamental element for the development of life in the city and a factor for the improvement of the city's social capital (Blečić et al., 2015; Frank et al., 2010; Talen and Anselin, 1998).

The multidimensional nature of the concept (Forsyth, 2015) entails different implications in designing public policies, especially with respect to the factors considered as determinants for its development. For this reason, there is not a single set of criteria scientifically recognised to analyse walkability. For example, Cervero and Kockelman

(1997) proposed the ‘3Ds layout’ (density, diversity and design), a list enlarged by Ewing and Cervero (2010) and Lee and Moudon (2006) with behavioural aspects and urban design elements. Gardner et al. (1996) proposed a set of five criteria named ‘5Cs’ (connected, convenient, comfortable, convivial and conspicuous), while Ewing and Handy (2009) consider both urban design factors and environmental aspects that can influence the whole experience of walking (imageability, enclosure, human scale, transparency, complexity).

The decision analysis methods used to study walkability and the relations among individuals and the context, are usually a set of indicators or a synthetic index calculated for different areas of a city [for example, walkscore or walkshed methods, (Frank et al., 2010; Sundquist et al., 2011; Iacono et al., 2010)], logit models are used to estimate the probability of walking and cycling (Cervero and Duncan, 2013) and multilevel and regression models to verify the relations among factors that influence the walkability and people’s behaviour (Lee and Moudon, 2006; Owen et al., 2007; Sundquist et al., 2011). Rarely are used methods more dynamic, aimed to analyse and to estimate the processes that influence behaviour of individuals in space, as the multi-agent models does. An interesting example is given by Crooks et al. (2015) that proposed a scene-and activity-aware agent-based model aimed to collect scene activity information as spatiotemporal trajectories for simulating and predicting pedestrian movement into the ABM model. They used rules deducted by observed behaviour and implemented these information with data from walkability literature to define ABM rules. Also, Yang et al. (2011) proposed a spatial agent-based model that simulate adults’ behaviour of walking in a city. They simulate the model in a 64 km^2 area, considering two environmental properties of space (safety and aesthetics) that affect people choice to walk (for work, basic needs or for leisure) and a set of individual characteristics: age, sex, walking ability, attitude towards walk and home location.

2.1 Model structure

The model is more focused on the habit of walking and what are those urban factors that decision-makers can act upon so as to incentivise citizens to walk more. For that reason, the model simulates an urban environment and how its citizens move in the city.

In more detail, the simulated urban environment consists of homes, places of work and commercial centres for leisure that the simulated citizens go to. Furthermore, in the environment there are three available means of transportation:

- walking through the city’s pedestrian network (or walking routes)
- public transportation in the form of buses or trams
- use of private cars.

The citizens of the simulated city are the agents of the model and must:

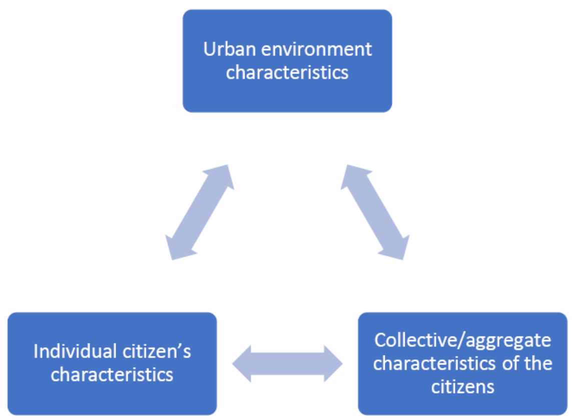
- Decide whether they must move towards their place of work or their home.
- Stay at their respective places (home or work) until the appropriate amount of simulated time has passed.
- Take a decision on the means of transportation that will be used.

- Perform the movement:
  a If that movement is walking then the agent must decide which path to follow.
  b If not the agent chooses one of the other available means of transportation

The last action of the agents adds an additional layer to the model; building on the work by Grider and Wilensky (Grider and Wilensky, 2015), the model can be used to investigate which walking paths (or routes) the agents prefer to move to and from their homes and how they can be affected by decisions of policy-makers. Thus, a spatial element is also added that can offer insights into what drives citizens to their choice not only of walking but also of the route they walk on.

Each agent's decisions and actions affect the environment: for example, how many private cars circulate affect the CO^2 emissions and the pollution level. On the other hand, the state of the environment affects the individual agents' decisions and actions. Thus, a loop is formed in which the characteristics and actions of each individual affect the characteristics of the entire population of agents, which affects the characteristics of the environment, which finally affects back both the individual and collective characteristics and actions of the citizens. Figure 1 illustrates the loop.

Figure 1 The core loop that illustrates the relationship between the agents and the simulated urban environment (see online version for colours)



With the purpose of being used as a learning tool for decision-makers, the model allows different possibilities of actions by the users. These actions can be grouped into two categories:

- Actions that act on the urban environment in general. In this model, we propose a first set of possible actions in order to implement the conduciveness of walking. These are not exhaustive, but useful to understand how the environmental opportunities conditions affect people choices. These are:
  a Walking routes. With this particular option the user of the model can decide to increase or decrease the amount of walking routes that are available to the agents (measured in kilometres).

b Number of public means of transportation. With this option the user can increase the number of public means of transportation (buses or trams) and increase the attractiveness of public transportation. Hence, it increases the possibilities to reach different opportunities (services, work, etc.) in the city.

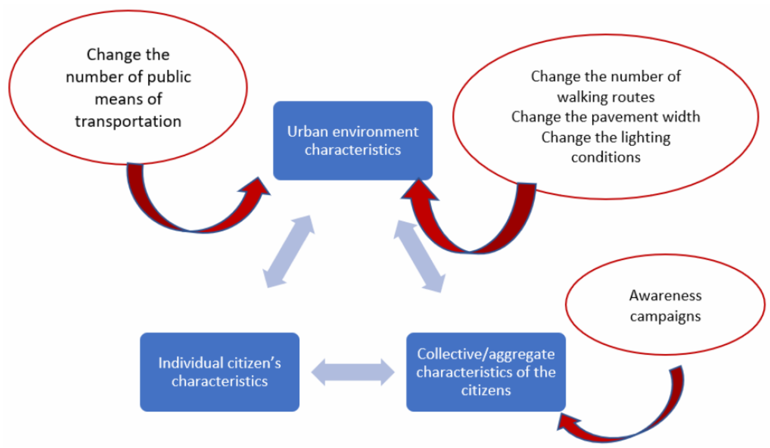
c General pavement width. With this option the user can increase the width of the pavements. It can be considered as a further incentive for agents to decide to walk, since better walking conditions will increase the attractiveness of walking as an option.

d General lighting conditions. It is similar to the previous options and can increase the attractiveness of walking, since better lighting conditions in the roads provide some levels of safety and security to people that choose to walk on.

- Actions that act on the population of agents. These are immaterial actions that can influence peoples' choices to move in the city. Such an example of an immaterial policy is an awareness campaign.

  a Awareness campaign: it is a theoretical variable whose purpose is to simulate the effect that an extensive campaign towards the avoidance of using private cars can have on the population. It takes values between 0 and 1 and it can be considered as a measure of the intensity (and success) of the campaign.

Figure 2 Key actions that can be performed by the user in the model (see online version for colours)



As mentioned already in the options above, the agents use the notion of attractiveness both for a transport mean, whether or not they will use it, and the choice for a particular commercial centre to attend. Thus, several factors contribute to that attractiveness and consequently to the people's choices.

- For walking, the variables that contribute to its attractiveness are:

  a distance between home and work

  b walking routes

  c pavement width

- d lighting conditions
- e awareness campaign.

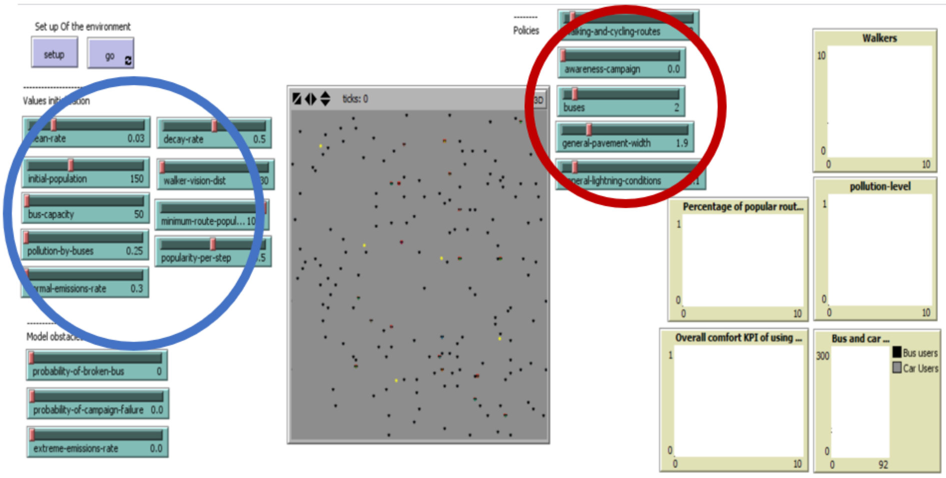
- For public transportation:
  - a Distance between home and work.
  - b Comfort of public transportation (that is affected by the number of public transportation vehicles that circulate).
  - c Awareness campaign.

- For the use of private cars:
  - a distance
  - b if the above options are deemed as not attractive enough the agents fall into the use of private cars.

- For the commercial centres
  - a How many people have visited it (popularity of the commercial centre).
  - b Distance from each agent’s home.
  - c How the area around the park increases attractiveness through:
    - 1 walking routes
    - 2 lightning conditions
    - 3 pavement width, etc.

The model was simulated with the Netlogo software and its graphical user interface can be observed below (Wilensky, 1999).

Figure 3 Graphical user interface of the model (see online version for colours)



The sliders that are inside the circle in red are variables that initialise the conditions of the model. They include a variety of factors that act not only on the environment but also on the agents. The sliders that are inside the red circle are the options/actions with whom the user can act on and study the effects of in the model.

Below, the sliders that initialise the model, there are three sliders that incorporate randomness (and diverse scenario settings) in the model. These are:

- Probability of broken bus: this value determines the probability that the increase of means of public transportation is successful. When there are more than two vehicles of public transportation, the model calculates at each time step a random number and if that number is lower than the probability of broken bus, then the total number of public transportation vehicles decreases by one.
- Probability of campaign failure: this variable works in the same way as the one above, with the only difference being that it acts upon the variable awareness campaign (if the value of awareness campaign is above 0.2, then the model at each time step calculates a random number and if that is lower than the probability of campaign failure, then the awareness campaign is reduced by 0.05).
- Extreme emissions rate: this variable introduces an extreme scenario in the game. At certain point in the simulation time, the emissions increase by the number that is depicted in the slider and the user can study and investigate how this extreme scenario can affect the agents' behaviour.

All these scenarios can be adapted with respect to the study of probabilities of these events in a particular urban environment and with specific awareness policies.

3 Results

The model offers the possibility of performing an array of experiments with different values for the parameters of the policy variables. As a result, Table 1 shows the variables that were changed for the experiments along with their min and max values.

Table 1 Name of variables that changed along with their min and max values

Variable	*Min value*	*Max value*
Awareness campaign	0	0.5
General pavement width	1.9	2.8
General lightning conditions	1.1	1.5
Number of buses	2	5
Walking routes	2	5

For the various combinations of the values of the variables, 32 runs of the model were performed and the main indicators that were studied were the variables:

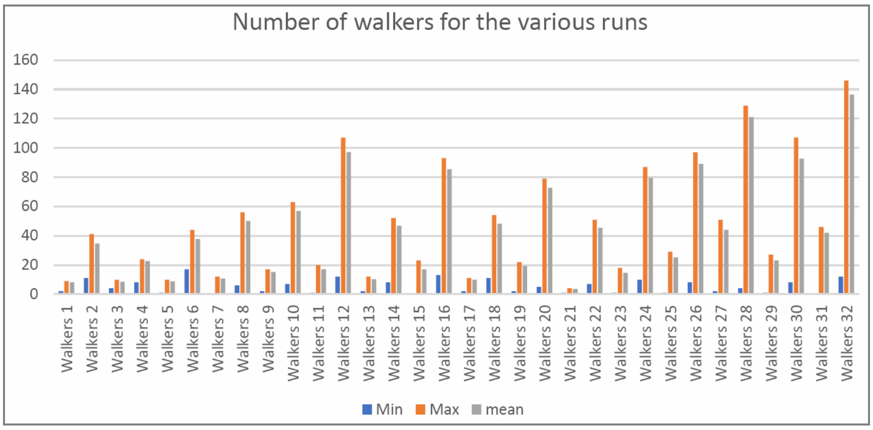
- Number of people that walked
- The percentage of the environment that formed a favourite walking path compared to the total area of the simulated city. This indicator gives an overview of how conducive to walking is the simulated environment to the citizens, incentivising them not only to walk but also form popular walking paths.
- Mean attractiveness of the commercial sites/malls.

The results for the three indicators will be analysed separately in the next sections.

3.1 Walkers

The first indicator focuses on the number of people that choose walking as the preferred mean of transportation. For each scenario, the number of agents that make the particular choice, by comparing the attractiveness of the various means of transportation, is calculated. This number illustrates how many from the general population of agents that must perform a movement, at any given time step, choose to walk, due to the attractiveness of walking that takes the largest value at the given time step. The number walkers in the simulated environment for all the experiments is illustrated in Figure 4.

Figure 4 Min, max and average value of walkers for the 32 runs (see online version for colours)



The figure illustrates the minimum, maximum and average value of the number of walkers for each of the 32 runs that were performed. It can be observed that the largest average value is achieved for the runs 12, 16, 24, 26, 28 30 and 32. For these runs, the combinations of the variables that change are:

Table 2 Combinations of the variables that produce the highest average of walkers

	Run 12	*Run 16*	*Run 24*	*Run 26*	*Run 28*	*Run 30*	*Run 32*
Awareness campaign	0	0	0.5	0.5	0.5	0.5	0.5
General pavement width	2.8	2.8	1.9	2.8	2.8	2.8	2.8
General lightning conditions	1.5	1.5	1.5	1.1	1.5	1.1	1.5
Number of buses	2	5	5	2	2	5	5
Walking routes	5	5	5	5	5	5	5
Average number of walkers	97.233	85.479	79.47	89.05	121.07	92.64	136.48

Firstly, it can be observed that the number of walking routes (in kilometres) is always five (the highest value of the runs) for the experiments that yield the highest number of walkers. As a result, the walking route is an important factor in increasing the walkability of an urban environment. Secondly, when the values of the other variables are high then the number of walkers increases, unsurprisingly, since all of these factors contribute to the incentivisation of the citizens to walk. Furthermore, a larger pavement width is more influential than a more intensive awareness campaign (see for example runs 12 and 24), demonstrating that citizens might need to see the change in the environment in order to adapt to a lifestyle of walking. Finally, when the number of buses receives its highest value (and the other variables are not maximised) then part of the population that would walk to its destination uses public means of transportation.

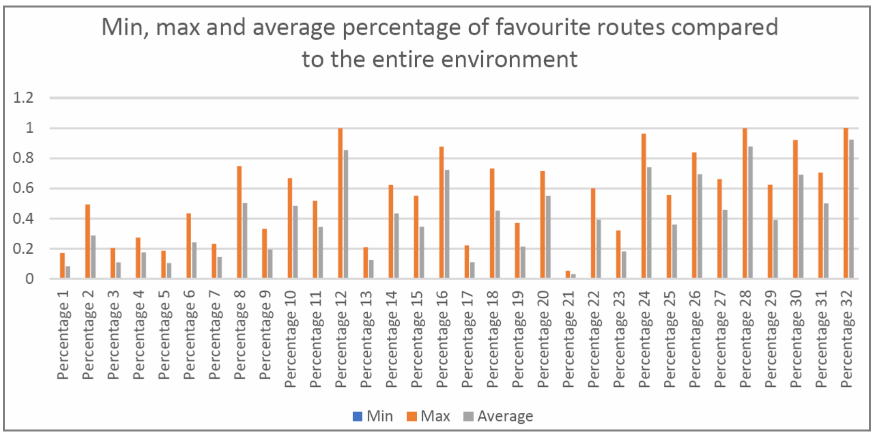
Thus, the array of the different scenarios confirmed that the higher the number of the factors that contribute to the experience of walking the larger the number of people that actually walk. Furthermore, the number of walkers increases by policies that show a tangible change in the urban environment (like an increase in the number of walking routes or better pavement conditions) rather than by policies that are more abstract in nature, whose results cannot be observed in the environment (like an awareness campaign). The results indicate that potential real-life policies should include tangible changes, since the virtual agents seem to adapt and accept them faster.

3.2 Favourite walking paths

The next indicator under study is the percentage of the urban environment that can be considered as part of a favourite walking route among the simulated citizens. It is a measure of attractiveness of the entire urban environment and during a simulation it remains active (i.e., favourite) the more people walk across it during the simulated time.

The software that was used for the simulation, includes spatial characteristics of an environment in the form of patches (can be considered as pixels). Thus, agents that choose to walk to their destination must make a choice over which patches they will pass in order to reach their destination. As a result, as an agent passes over a particular patch, it changes its attributes (a popularity index that decreases over time and increases by the number of agents that pass through the particular patch). A favourite path is formed when patches of the environment of Netlogo are chosen consistently from agents as part of their route to their destination. Consequently, the indicator that was chosen for the study, calculates what is the percentage of patches that have a popularity score above a particular threshold over the total number of patches of the simulated environment.

Figure 5 Min, max and average value of the percentage of the environment that is part of favourite walking routes (see online version for colours)



The array of scenarios produced the following summarised statistics for that percentage.

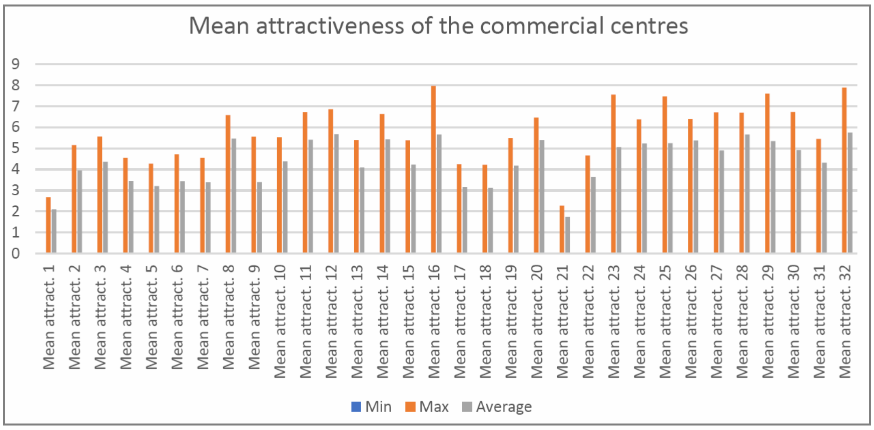
The figure highlights the connection with the previous indicator since the runs that produced the highest average number of walkers, also yielded the best results for the percentage of the environment that is considered a favourite route by those walkers. As a result, a pattern emerges from the model in the form of a feedback loop; the more people walk, the highest the probability that they will develop favourite routes. As the popularity of these routes increases, more people will walk across them hence increasing again the routes' popularity.

3.3 Attractiveness of commercial centres

The final indicator of the model concerns the attractiveness of the commercial centres of the model (places that people go for leisure). In the model that was developed, five commercial centres were inserted that can be considered malls that agents go for leisure and/or shopping. The mechanism that determines whether agents will go to a particular centre works as follows: when the agents are in the patch that is considered their home, they have to make a choice where their next movement will be. The model randomly draws a number between 0 and 3 and if that number is equal to 1 then the particular agent will choose a commercial centre as its destination. Which centre that will be, depends on its attractiveness, a concept that is determined by how many agents have visited it in the past along with the attractiveness of the surrounding area.

The results for the various experiments/runs are demonstrated in Figure 6.

Figure 6 Min, max and average values for the attractiveness of the commercial centres (see online version for colours)



From Figure 6, it can be observed that almost all the runs produce good results for the mean attractiveness of the commercial centres. Thus, from a first glance the attractiveness of a place of leisure is not strictly connected to the number of walkers. Since all runs produce similar results it would be interesting to study the two runs that yielded the lowest results (runs 1 and 21).

The factors that varied for the two runs and their values are depicted in Table 3.

The table shows that the attractiveness of the commercial centres reaches its lowest points when the policies of general pavement width, general lightning conditions and number of walking routes have their lowest values. As a result, the attractiveness may not be strictly connected to the number of walkers in the urban environment, but it appears to be affected by the conditions that affect the attractiveness of walking. While the first assertion comes to no surprise, since people do not always go for leisure by foot, the second assertion demonstrates that poor conditions in the environment act may negatively in its business sector.

Table 3 Combinations of variables that produce the lowest values of the attractiveness of the commercial centres

	Run 1	*Run 21*
Awareness campaign	0	0.5
General pavement width	1.9	1.9
General lightning conditions	1.1	1.1
Number of buses	2	5
Walking routes	2	2
Mean attractiveness of commercial centres	2.098	1.731

Hence, a counterintuitive result emerges from the model; keeping the conditions of an urban environment in poor shape might also have a negative effect on the commercial activity of that particular environment. As a result, potential policies that stimulate the factors that can incentivise people to walk can also have economic benefits for the city.

4 Conclusions

The purpose of the paper was to use agent-based simulation to investigate how the choice of transportation by people can affect the urban environment both in the short- and long-term and how the urban environment can affect the behaviour of people with regards to walking. An agent-based model was built that simulated an urban environment. The agents of the model can be considered as its citizens that perform a number of movements throughout the simulated day. These movements are to and from their homes, places of work and places of leisure (commercial centres). In the model there are three available modes of transportation: walking, public transportation means and private transportation. Each agent decides on which mean to use based on several factors (qualitative and quantitative) that determine the general attractiveness of each particular option.

The notion of attractiveness is also used in the choice of which commercial centre will be the one that the agents will go to. To study the behaviour of the model, three indicators were used: the number of people that choose walking, the percentage of the environment that is considered ‘favourite route’ by the agents and the average attractiveness of the commercial centres.

An array of scenarios was simulated by providing different values for the variables that are labelled as ‘policies’ in the model. The main findings of the simulations were that the higher the value of those factors that, in theory, are supposed to increase the walkability of an area, the higher the number of agents that actually walk. Furthermore, the agents of the model chose to walk in higher numbers, when the values of the variables that represent tangible changes were increased (i.e., pavement and lightning conditions, number of walking routes), particularly when compared with policies that do not produce tangible results (i.e., awareness campaigns). These results coincide with the results of the second indicator, percentage of the urban environment that entails the agents' favourite routes. From those two indicators emerges an important pattern in the model in the form of a feedback loop; the more agent walk, the highest the probability that they will develop favourite routes. As the popularity of these routes increases, more agents will walk across them hence increasing again the routes' popularity.

Regarding the average attractiveness of the commercial centres, the results showed that the attractiveness may not be strictly connected to the number of walkers in the urban environment, but it is affected by the conditions that affect the attractiveness of walking. As a result, another pattern emerges in the model: by keeping the factors that can incentivise agents to walk at low levels seems to have a negative effect on the implicit economic activity of the model.

Future directions of the research include the expansion of the model in several ways. Firstly, more factors and different equations could be used to determine how the environment affects the behaviour of agents with regards to walking. Secondly, the movement of the agents could become more complex and be connected with the time of day. For example, in the morning there would be a higher probability that each agent would have to go to work, while in the afternoon that probability would be to go to a commercial centre. Moreover, an implementation of the model can be done with the analysis of the resources needed for the development both of an awareness campaign or of a walkable environment (in monetary terms but also in terms of changes in the use of the street environment, like the elimination of parking along the street, or in terms of health improvement of people living in a city) in order to understand the trade-off among policies and among the different interests in the city.

Furthermore, more complex and extensive analyses could be performed to determine what is the effect level of each of the variables to the three indicators. In that direction, the spatial characteristics of the places of work and commercial centres could be investigated with the purpose of offering insights into urban planning. Connecting the model with GIS data, offers the possibility to introduce the spatial characteristics of a real environment and the preferences of such population that live in the city, and compare those results to the experimental ones that were used in the model.

References

Blečić, I., Cecchini, A., Congiu, T., Fancello, G. and Trunfio, G.A. (2015)' Evaluating walkability: a capability-wise planning and design support system', *Int. J. Geogr. Inf. Sci*, Vol. 29, DOI: 10.1080/13658816.2015.1026824.

Cervero, R. and Duncan, M. (2003) 'Walking, bicycling, and urban landscapes: evidence from the San Francisco Bay area', *American Journal of Public Health*, Vol. 93, No. 9, pp.1478–1483.

Cervero, R. and Kockelman, K. (1997) 'Travel demand and the 3Ds: density, diversity, and design', *Transp. Res. Part D Transp. Environ*., Vol. 2, pp.199–219, DOI: 10.1016/S1361-9209(97)00009-6.

Clifton, K.J., Livi Smith, A.D. and Rodriguez, D. (2007) 'The development and testing of an audit for the pedestrian environment', *Landscape and Urban Planning*, Vol. 80, Nos. 1–2, pp.95–110.

Crooks, A., Croitoru, A., Lu, X., Wise, S., Irvine, J.M. and Stefanidis, A. (2015) 'Walk this way: improving pedestrian agent-based models through scene activity analysis', *ISPRS International Journal of Geo-Information*, Vol. 4, No. 3, pp.1627–1656.

Ewing, R. and Cervero, R. (2010) 'Travel and the built environment: a meta-analysis', *J. Am. Plan. Assoc*., Vol. 76, pp.265–294, DOI: 10.1080/0194436100376676.

Ewing, R. and Handy, S. (2009) 'Measuring the unmeasurable: urban design qualities related to walkability', *J. Urban Des*., Vol. 14, pp.65–84, DOI: 10.1080/13574800802451155.

Forsyth, A. (2015) 'What is a walkable place? The walkability debate in urban design', *Urban Des. Int*., Vol. 20, pp.274–292, DOI: 10.1057/udi.2015.22.

Forsyth, A., Hearst, M., Oakes, J.M. and Schmitz, K.H. (2008) 'Design and destinations: factors influencing walking and total physical activity', *Urban Stud*., Vol. 45, pp.1973–1996, DOI: 10.1177/0042098008093386.

Frank, L.D., Sallis, J.F., Conway, T.L., Chapman, J.E., Saelens, B.E. and Bachman, W. (2006) 'Many pathways from land use to health', *J. Am. Plan. Assoc*., Vol. 72, pp.75–87, DOI: 10.1080/01944360608976725.

Gardner, K., Johnson, T., Buchan, K. and Pharoah, T. (1996) 'Developing a pedestrian strategy for London', in *Transport Policy and its Implementation: Proceedings of Seminar B Held at the PTRC European Transport Forum*, Brunel University, England, 2–6 September 1996, *PTRC Education and Research Services on behalf of Planning and Transport Research and Computation International Association*, London, p.400.

Grider, R. and Wilensky, U. (2015) 'Netlogo Paths model', *Center for Connected Learning and Computer-Based Modeling*, Evanston, Illinois [online] http://ccl.northwestern.edu/netlogo/models/Paths (accessed 1 October 2017).

Hajna, S., Dasgupta, K., Halparin, M. and Ross, N.A. (2013) 'Neighborhood walkability: field validation of geographic information system measures', *Am. J. Prev. Med*., Vol. 44, pp.e55–e59, DOI: 10.1016/j.amepre.2013.01.033.

Handy, S.L. and Niemeier, D.A. (1997) 'Measuring accessibility: an exploration of issues and alternatives', *Environ. Plan. A*, Vol. 29, pp.1175–1194, DOI: 10.1068/a291175.

Hansen, W.G. (1959) 'How accessibility shapes land use', *J. Am. Inst. Plann*., Vol. 25, pp.73–76, DOI: 10.1080/01944365908978307.

Harvey, D. (2003) 'The right to the city', *Int. J. Urban Reg. Res*., Vol. 27, pp.939–941, DOI: 10.1111/j.0309-1317.2003.00492.x.

Iacono, M., Krizek, K.J. and El-Geneidy, A. (2010) 'Measuring non-motorized accessibility: issues, alternatives, and execution', *J. Transp. Geogr*., Vol. 18, pp.133–140, DOI: 10.1016/j.jtrangeo.2009.02.002.

Jacobs, J. (1961) *The Death and Life of Great American Cities*, 1st ed., Random House, New York.

Kelly, C.E., Tight, M.R., Hodgson, F.C. and Page, M.W. (2011) 'A comparison of three methods for assessing the walkability of the pedestrian environment', *J. Transp. Geogr*., Vol. 19, pp.1500–1508, DOI: 10.1016/j.jtrangeo.2010.08.001.

Lee, C. and Moudon, A.V. (2006) 'The 3Ds + R: quantifying land use and urban form correlates of walking', *Transp. Res. Part D Transp. Environ*., Vol. 11, pp.204–215, DOI: 10.1016/j.trd.2006.02.003.

Lefebvre, H. (1996) *Writings on Cities*, English ed., Blackwell Publishers Ltd., Oxford.

Livi, A.D. and Clifton, K.J. (2004) 'Issues and methods in capturing pedestrian behaviors, attitudes and perceptions: experiences with a community-based walkability survey', *Transp. Res. Board Annu. Meet*. 17pp.

Lynch, K. (1960) *The Image of the City*, Vol. 11, MIT Press, Cambridge MA.

Lynch, K. (1981) *A Theory of Good City Form*, The MIT Press, Cambridge, Massachusetts.

Owen, N., Cerin, E., Leslie, E., duToit, L., Coffee, N., Frank, L.D., Bauman, A.E., Hugo, G., Saelens, B.E. and Sallis, J.F. (2007) 'Neighborhood walkability and the walking behavior of Australian adults', *Am. J. Prev. Med.*, Vol. 33, pp.387–395, DOI: 10.1016/j.amepre.2007.07.025.

Páez, A. (2013) 'Mapping travelers' attitudes: does space matter?', *J. Transp. Geogr.*, Vol. 26, pp.117–125, DOI: http://doi.org/10.1016/j.jtrangeo.2012.09.002.

Porta, S. and Renne, J.L. (2005) 'Linking urban design to sustainability: formal indicators of social urban sustainability field research in Perth, Western Australia', *URBAN Des. Int.*, Vol. 10, pp.51–64, DOI: 10.1057/palgrave.udi.9000136.

Sundquist, K., Eriksson, U., Kawakami, N., Skog, L., Ohlsson, H. and Arvidsson, D. (2011) 'Neighborhood walkability, physical activity, and walking behavior: the Swedish neighborhood and physical activity (SNAP) study', *Soc. Sci. Med.*, Vol. 72, pp.1266–1273, DOI: 10.1016/j.socscimed.2011.03.004.

Talen, E. and Anselin, L. (1998) 'Assessing spatial equality: an evaluation of measures of accessibility to public playgrounds', *Environment and Planning*, Vol. 30, No. 4, pp.595–613.

Walk Score (2016) [online] http://www.walkscore.com/ (accessed 12 December 2016).

Walkshed (2016) [online] http://www.walkshed.org/ (accessed 12 December 2016).

Wilensky, U. (1999) *Center for Connected Learning and Computer-Based Modeling*, Netlogo. Evanston, Illinois.

Wilensky, U. and Rand, W. (2015) 'An introduction to agent-based modeling', *Modeling Natural, Social and Engineered Complex Systems with Netlogo*, Massachusetts Institute of Technology Press, Cambridge, MA.

Yang, Y., Roux, A.V.D., Auchincloss, A.H., Rodriguez, D.A. and Brown, D.G. (2011) 'A spatial agent-based model for the simulation of adults' daily walking within a city', *American Journal of Preventive Medicine*, Vol. 40, No. 3, pp.353–361.